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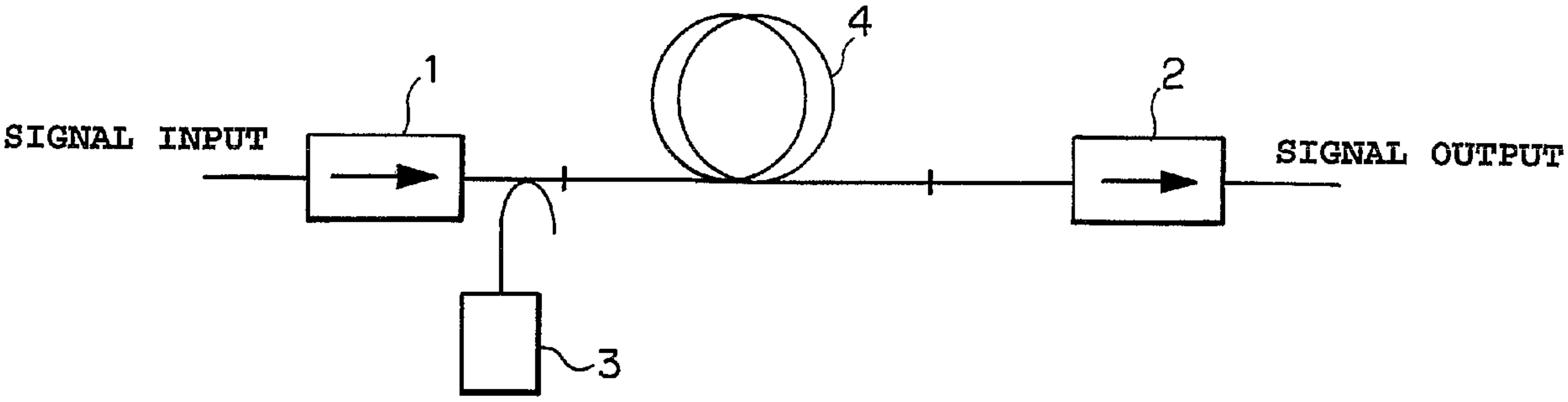


(57) **Abrégé/Abstract**:

An optical amplification medium doped with Er^{3+} ions is selected from the group of a fluoride glass, a chalcogenide glass, a telluride glass, a halide crystal, and a lead oxide based glass. The Er^{3+} ions are excited by light of at least one wavelength in the range of 0.96 μm to 0.98 μm. A laser or an optical amplifier includes this optical amplification medium doped with Er^{3+} ions. Furthermore, an optical amplification method performs an optical amplification using the optical amplifier having the optical amplification medium doped with Er^{3+} ions. Thus, the laser to be applied in the field of optical communication, the optical amplifier having the characteristics of low noise and high gain, and the optical amplification method can be provided.

ABSTRACT OF THE DISCLOSURE

An optical amplification medium doped with Er^{3+} ions is selected from the group of a fluoride glass, a chalcogenide glass, a telluride glass, a halide crystal, and a lead oxide based glass. The Er^{3+} ions are excited by light of at least one wavelength in the range of 0.96 μm to 0.98 μm. A laser or an optical amplifier includes this optical amplification medium doped with Er^{3+} ions. Furthermore, an optical amplification method performs an optical amplification using the optical amplifier having the optical amplification medium doped with Er^{3+} ions. Thus, the laser to be applied in the field of optical communication, the optical amplifier having the characteristics of low noise and high gain, and the optical amplification method can be provided.

The present invention relates to lasers, optical amplifiers with the properties of low noise and high gain, and amplification methods.

In recent years, the development of an optical amplifier, in which an optical fiber having a core doped with a rare earth element is provided as an amplification medium, has been worked on for the applications in the field of optical communication. Particularly, an erbium (Er^{3+}) -doped fiber amplifier (EDFA) has been developed, and also the development efforts are being made to increase applications of the EDFA to an optical communication system.

Recently, a wavelength division multiplexing (WDM) technique has been studied extensively to cope with the diversification of communication service to be expected in coming years. The WDM technique is an optical communication technique that uses a system of multiplexing wavelengths for the sake of an effective use of available transmission medium leading to enlarge a transmission volume. One of the characteristics required to the EDFA applied in the WDM technique is a small variation to an amplification gain with respect to a signal wavelength. Because, there are power differentials among optical signals which are transitionally amplified by passing through a multi-stage arrangement of the EDFAs, so that it is difficult to perform the signal transmission with uniform characteristics maintained across all of the wavelengths being used. Presently, therefore, the EDFA showing a flat gain region with respect to the predetermined wavelengths has been investigated by persons skilled in the art.

Attention is being given to an erbium (Er^{3+})-doped fluoride fiber amplifier (F-EDFA) as a most promising candidate as the EDFA, in which a fluoride-based fiber is used as a host of Er^{3+}. The F-EDFA is characterized by its emission spectrum caused by a transition from the $^4I_{13/2}$ level to the $^4I_{15/2}$ level of Er^{3+} ions in the fluoride glass at a wavelength band of 1.55 µm.

Fig. 1 shows a typical amplitude spontaneous emission (ASE) spectrum of the F-EDFA. This figure also shows the ASE spectrum of an Er^{3+}-doped silica glass fiber (S-EDFA). As shown in the figure, the emission spectrum (a full line in the figure) of the F-EDFA is broader than the emission spectrum (a dashed line in the figure) of the S-EDFA. In addition, the response curve of the F-EDFA is smoother than that of the S-EDFA and is flat on top without any steep portion depended on a wavelength in the predetermined wavelength region (M. Yamada et al., IEEE Photon. Technol. Lett., vol. 8, pp. 882-884, 1996). Furthermore, experiments of wavelength division multiplexing have been carried out using multi-staged F-EDFAs, for example a cascade configuration with a 980 nm pumped S-EDFA and a 1480 nm pumped F-EDFA (M. Yamada et al., IEEE Photon. Technol. Lett., vol. 8, pp 620-622,1996).

In spite of the above development efforts, the F-

EDFA has a problem that it cannot reduce a noise figure (NF) as much as that observed in the S-EDFA because of the following reasons.

Fig. 2 is an energy diagram of Er^{3+}. A phonon energy takes a value of the order of 1,100 cm^{-1} when the EDFA uses a silica optical fiber as an amplification medium (i.e., in the case of the S-EDFA), so that a favorable population inversion between the $^4I_{13/2}$ level and the $^4I_{15/2}$ level can be formed by an efficient excitation to the $^4I_{13/2}$ level as a result of a phonon emitted relaxation from higher energy levels to the $^4I_{13/2}$ level after exciting to the $^4I_{11/2}$ level by 0.98 μm pump light (Fig. 2 (A)). Consequently, the S-EDFA enables a reduction in the NF to about 4 dB, which is close to a quantum limit (3 dB). On the other hand, the F-EDFA cannot perform an excitation to the $^4I_{13/2}$ level using a transmission from the $^4I_{15/2}$ level to the $^4I_{11/2}$ level because of its low phonon energy. That is, the F-EDFA has a phonon energy of about 500 cm^{-1} which is almost half of the S-EDFA's phonon energy, so that it is difficult to cause a phonon emitted relaxation from the $^4I_{11/2}$ level to the $^4I_{13/2}$ level and to obtain an amplification gain by 0.98 μm pump light. In this case, therefore, an amplification gain at a wavelength of 1.55 μm is obtained by directly exciting from the $^4I_{15/2}$ level to the $^4I_{13/2}$ level using light at a pump wavelength of about 1.48 μm (Fig. 2 (B)). However, this kind of the excitation is an initial excitation of the ground energy level to the higher energy level, so that it is difficult to make a favorable population inversion in which the number of Er^{3+} ions at higher energy levels exceed those at lower energy levels, resulting in the high NF (i.e., 6 to 7 dB).

Therefore, the conventional F-EDFA with favorable noise characteristics has not been realized, compared with that of the S-EFDA.

It is an object of the invention to solve the above problem (i.e., high noise figure) associated with conventional F-EDFA and to provide a laser, an optical amplifier with the properties of low noise, and high and flat gain, and an amplification method.

In a first aspect of the present invention, there is provided an optical amplification method that uses an optical amplification medium doped with Er^{3+} ions, comprising a step of exciting the Er^{3+} ions by light of at least one wavelength in a range of 0.96 μm to 0.98 μm, where the optical amplification medium is selected from a group of a fluoride glass, a chalcogenide glass, a telluride glass, a halide crystal, and a lead oxide based glass.

Here, the optical amplification medium may be in a shape of a fiber.

In a second aspect of the present invention, there is provided an optical amplifier having an optical amplification medium doped with Er^{3+} ions, wherein the optical amplification medium is selected from a group of a fluoride glass, a chalcogenide glass, a telluride glass, a halide crystal, and a lead oxide based glass, and the Er^{3+} ions is excited by light of at least one wavelength in a range of 0.96 µm to 0.98 µm.

The optical amplification medium may be in a shape of a fiber.

The optical amplifier may further comprise:

a light source for an excitation to $^4I_{13/2}$ level.

In a third aspect of the present invention, there is provided an optical amplification method that uses an optical amplifier having: an optical amplification medium doped with Er^{3+} ions and selected from a group of a fluoride glass, a chalcogenide glass, a telluride glass, a halide crystal, and a lead oxide based glass; a light source for exciting the Er^{3+} ions with an oscillation wavelength in a range of 0.96 µm to 0.98 µm; and a light source for an excitation to $^4I_{13/2}$ level, comprising steps of:

launching pump light, which is emitted in the same direction as that of launching a signal light into the optical amplification medium from the light source for exciting the Er^{3+} ions with an oscillation wavelength in a range of 0.96 µm to 0.98 µm, into the optical amplification medium; and

launching light, which is emitted in an opposite direction of the pump light, from the light source for an excitation to $^4I_{13/2}$ level into the optical amplification medium.

Here, the optical amplification medium may be in a shape of a fiber.

In a fourth aspect of the present invention, there is provided an a laser having an optical amplification medium doped with Er^{3+} ions and a pump light source for an excitation of the optical amplification medium and using an induced emission of Er^{3+} ions from $^4I_{13/2}$ level to $^4I_{15/2}$ level, wherein

the pump light source includes at least a first light source and a second light source, which emit light at different wavelengths, and

the first light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level of the Er^{3+} ions and an energy level higher than the $^4I_{13/2}$ level.

Here, the first light source may be provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level and one energy level selected from a group of $^4I_{11/2}$ level, $^4I_{9/2}$ level, $^4F_{9/2}$ level, and $^4S_{3/2}$ level of the Er^{3+} ions.

The second light source may be provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and one energy level selected from a group of $^4I_{11/2}$ level and $^4F_{9/2}$ level of the Er^{3+} ions.

The laser may further comprise a third light source, wherein the first light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level and $^4S_{3/2}$ level of the Er^{3+} ions;

the second light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{11/2}$ level of the Er^{3+} ions; and

the third light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{13/2}$ level of the Er^{3+} ions.

The first light source may be provided as a light source for emitting light at a wavelength of 0.82 μm to 0.88 μm; and

the second light source may be provided as a light source for emitting light at a wavelength of 0.96 μm to 0.98 μm.

The optical amplification medium doped with Er^{3+} ions may be selected from a group of a fluoride fiber doped with Er^{3+} ions, a chalcogenide fiber doped with Er^{3+} ions, a telluride fiber doped with Er^{3+} ions, and a halide crystal doped with Er^{3+} ions.

In a fifth aspect of the present invention, there is provided an optical amplifier at least comprising:

an optical amplification medium doped with Er^{3+} ions;

means for inducing and isolating signal light at a wavelength of 1.5 μm into the optical amplification medium; and

a pump light source for an excitation of the optical amplification medium, wherein

the pump light source includes at least a first light source and a second light source, which emit light at different wavelengths, and

the first light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level of the Er^{3+} ions and an energy level higher than the $^4I_{13/2}$ level.

Here, the first light source may be provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level and one energy level selected from a group of $^4I_{11/2}$ level, $^4I_{9/2}$ level, $^4F_{9/2}$ level, and $^4S_{3/2}$ level of the Er^{3+} ions.

The second light source may be provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and one energy level selected from a group of $^4I_{11/2}$ level and $^4F_{9/2}$ level of the Er^{3+} ions.

The optical amplifier may further comprise a third light source, wherein

the first light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level and $^4S_{3/2}$ level of the Er^{3+} ions;

the second light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{11/2}$ level of the Er^{3+} ions; and

the third light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{11/2}$ level of the Er^{3+} ions.

The first light source may be provided as a light source for emitting light at a wavelength of 0.82 μm to 0.88 μm; and

the second light source may be provided as a light source for emitting light at a wavelength of 0.96 μm to 0.98 μm.

The second light source may be provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{13/2}$ level of the Er^{3+} ions.

The optical amplification medium doped with Er^{3+} ions may be selected from a group of a fluoride fiber doped with Er^{3+} ions, a chalcogenide fiber doped with Er^{3+} ions, a telluride fiber doped with Er^{3+} ions, and a halide crystal doped with Er^{3+} ions.

In a sixth aspect of the present invention, there is provided an optical amplifier that uses Er^{3+} ions as amplification active elements, comprising:

means for launching at least one light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{11/2}$ level of the Er^{3+} ions, at least one light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level and an energy level higher than the $^4I_{11/2}$ level of the Er^{3+} ions, and at least one light to be amplified by an induced emission transition from $^4I_{11/2}$ level to $^4I_{15/2}$ level into an amplification medium doped with the Er^{3+} ions from same direction.

Preferably, the light at a wavelength different from the signal light and corresponding to an energy difference between $^4I_{13/2}$ level and $^4I_{15/2}$ level of the Er^{3+} ions may be launched into the optical amplification medium from a direction different from the same direction.

In a seventh aspect of the present invention, there is provided an optical amplification method that uses Er^{3+} ions as amplification active elements, comprising a step of launching light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{11/2}$ level of the Er^{3+} ions, light at a wavelength corresponding to an energy difference between $^4S_{3/2}$ level and $^4I_{11/2}$ level of the Er^{3+} ions, and light to be amplified by an induced emission transition from $^4I_{13/2}$ level to $^4I_{15/2}$ level into an amplification medium doped with the Er^{3+} ions from same direction.

Here, the light at a wavelength different from the signal light and corresponding to an energy difference between $^4I_{13/2}$ level and $^4I_{15/2}$ level of the Er^{3+} ions may be launched into the optical amplification medium from a direction different from the same direction.

In an eighth aspect of the present invention, there is provided an optical amplification method that uses Er^{3+} ions as amplification active elements, comprising a step of launching light at a wavelength of 0.82 µm to 0.88 µm, light at a wavelength of 0.96 µm to 0.98 µm, and light to be amplified by an induced emission transition from $^4I_{13/2}$ level to $^4I_{15/2}$ level into an amplification medium doped with the Er^{3+} ions from same direction.

Fig. 1 is a typical amplitude spontaneous emission (ASE) spectrum of the F-EDFA;

Fig. 2 is an energy diagram of Er^{3+} for the conventional S-EDFA (A) and the conventional F-EDFA (B);

Fig. 3 is a graphical representation of the relationship between the wavelengths and the absorption or emission cross section with respect to the energy state between the $^4I_{15/2}$ level and $^4I_{11/2}$ level;

Fig. 4 is an energy diagram of Er^{3+} for the F-EDFA of the present invention;

Fig. 5 is a schematic block diagram of an optical amplifier using a Er^{3+} -doped ZrF_4-based fluoride fiber in accordance with the present invention;

Fig. 6 is a graphical representation of the relationship between the pump wavelengths and the signal gains with respect to the optical amplifier using the Er^{3+} -doped ZrF_4-based fluoride fiber of Fig. 5;

Fig. 7 is a schematic block diagram of an optical amplifier as one of the preferred embodiments of the present invention;

Fig. 8 is an energy diagram of Er^{3+} to be applied in the lasers and the optical amplifiers of the present invention, where (A), (B), (C), and (D) show different excitation ways of the Er^{3+};

Fig. 9 is a schematic block diagram of an optical amplifier as one of the preferred embodiments of the present invention;

Fig. 10 is a schematic block diagram of a laser as one of the preferred embodiments of the present invention;

Fig. 11 is a schematic block diagram of a laser as one of the preferred embodiments of the present invention;

Fig. 12 is a schematic block diagram of an optical amplifier as one of the preferred embodiments of the present invention;

Fig. 13 is a graphical representation of the relationship between the pump wavelengths and the excitation densities of the $^4S_{3/2}$ level.

Fig. 14 is a graphical representation of the relationship between the wavelengths and the absorption or emission cross section with respect to the energy state between the $^4S_{3/2}$ level and $^4I_{13/2}$ level;

Fig. 15 is a perspective diagram of a main portion of an optical amplifier in the type of an optical waveguide as one of the preferred embodiments of the present invention; and

Fig. 16 is an energy diagram of Er^{3+} with consideration given to the mutual interactions among the Er^{3+} ions.

Each laser, optical amplifier, and amplification method of the present invention is mainly characterized by employing at least one pump light at a wavelength in the range of 0.96 µm to 0.98 µm for the excitation of Er^{3+} from the ground level to the $^4I_{11/2}$ level because of the following reasons.

Fig. 3 is a graph representing the relationship between the pump wavelengths and the cross-sectional areas (in the figure, a full line shows an absorption cross section and a dashed line shows an induced emission cross section) with respect to an energy state between the $^4I_{15/2}$ level to $^4I_{11/2}$ level. In the wavelength region of over about 980 µm, as shown in the figure, the induced emission cross-section area (dashed line) becomes greater than the absorption cross section area (full line). Therefore an induced emission transition from the $^4I_{11/2}$ level to the $^4I_{15/2}$ level tends to occur more strongly compared with an absorption transition from the $^4I_{15/2}$ level to the $^4I_{11/2}$ level in that wavelength region, so that the excitation to the $^4I_{11/2}$ level cannot occur effectively. Alternatively, as clearly shown in the figure, the excitation to the $^4I_{11/2}$ level can effectively occur by pumping at a wavelength shorter than 980 µm. In this case, on the other hand, the pump ESA (Excited State Absorption) from the $^4I_{11/2}$ level to the $^4F_{7/2}$ level is more likely to take place. As shown in Fig. 4, however, the excitation to the $^4I_{13/2}$ level can be eventually attained because of the step of relaxing from the

$^4F_{7/2}$ level to the $^4I_{13/2}$ level.

(Embodiment 1)

Referring now to Fig. 5, there is shown a basic configuration of an optical amplifier having an Er^{3+}-doped ZrF_4-based fluoride fiber as one of the preferred embodiments of the present invention. For a more detailed explanation, an excitation spectrum (the pump wavelength dependency of the signal gain) on the above fiber is shown in Fig. 6.

The optical amplifier comprises two optical isolators 1, 2, a pump light source 3, and an Er^{3+}-doped ZrF_4-based fluoride fiber 4 sandwiched between the optical isolators 1, 2. In this embodiment, the fiber 4 is 25 μm in length with the cut-off wavelength of 1 m, and also a doping concentration of Er^{3+} in its core is 200 ppm. In this embodiment, furthermore, a signal wavelength is 1530 nm, an input signal power is -30 dBm, and a pump light power is 60 mW.

Depending on the above configuration of the optical amplifier, the maximum gain can be obtained at a pump wavelength of 970 nm. As shown in Fig. 6, however, a negative gain is observed at a pump wavelength of 980 nm. This wavelength is conventionally used for exciting Er^{3+} to the $^4I_{11/2}$ level, and thus we recognize that we cannot obtain the gain at the pump wavelength of 980 nm. Therefore, any wavelength in the range of 960 nm to 980 nm, preferably in proximity to 970 nm is effective to obtain a gain by exciting Er^{3+} to the $^4I_{11/2}$ level.

Then the amplification characteristics of the above fiber 4 is investigated by a forward excitation using pump light at a wavelength of 970 nm (i.e., the pump light is launched into the fiber 4 from the upstream side of the fiber 4 by the light source 3). In this case, the input signal power launched into the fiber 4 is -30 dBm. When the pump light power is 132 mW, an obtained gain at a wavelength of 1.53 µm is 30 dB and a noise figure (NF) is 4.5 dB. Also, the NF is 3.5 dB when the wavelength is 1.55 µm. When the above fiber 4 is excited by an pump light with the wavelength of 1.48 gm, an improvement degree of the NF is 1.5 µm or over with reference to the NF at 1.55 µm of 5 dB or over. In addition, we confirmed that the NF was improved (decreased) when the wavelength of the pump light was within the range of 960 nm to 980 nm, compared with that of exciting at 1.48 µm. Furthermore, the NF is improved by the excitation using two or more wavelengths in the range of 960 nm to 980 nm.

(Embodiment 2)

The same optical amplifier as that of Embodiment 1 is used in this embodiment to measure the NF by introducing WM signals at eight different wavelengths in the range of 1530 to 1560 nm. The input signal power launched into the optical amplifier is -20 dBm per one wavelength. When the excitation is performed with a total pump light power of 150 mW using the pump wavelength of

970 nm, the observed NF is 5 dB or less by introducing the WDM signals at the wavelengths in the range of 1530 to 1560 nm.

(Embodiment 3)

In this Embodiment, the amplification characteristics of an optical amplifier are estimated using the same WDM signals as those of Embodiment 2 except what follows. In this Embodiment, an optical amplifier is the same one as that of Embodiment 1 or 2 except that a bi-directional pump method is used for launching different pump light into the fiber 4. The method comprises the steps of applying pump light at wavelengths in the range of 960 to 980 nm from the front (i.e., the upstream side of the fiber 4 in the same direction as that of the signal light) and simultaneously applying pump light at a wavelength of 1480 nm from the rear (i.e., the downstream side of the fiber 4).

Fig. 7 shows a configuration of the optical amplifier. Comparing with a configuration of the optical amplifier shown in Fig. 5, an additional light source 5 for the excitation to the $^4I_{13/2}$ level is further installed in the optical amplifier and positioned at the downstream side of the Er^{3+}-doped fluoride fiber 4. The pump light power for the front is 50 mW, while the pump light power for the rear is in the range of 100 mW to 150 mW. In addition, the optical amplifier shows the NF of 5 dB or less for the wavelengths of 1530 nm to 1560 nm, allowing the gain excursion of 2 dB or less for the signal wavelength.

(Embodiment 4)

In each of Embodiments 1 to 3 described above, the amplification characteristics of the optical amplifier using the Er^{3+}-doped ZrF_4-based fluoride fiber as its amplification medium are evaluated. In this Embodiment, an amplification medium as a host of Er^{3+} is selected from the group of an InF_3-based fluoride fiber, a chalcogenide glass-based fiber, a TeO_2-based fiber, and a PbO-based fiber, instead of the ZrF_4-based fluoride fiber to prepare an optical amplifier. Then the optical amplifier having any one of the above fibers is subjected to the same experiments as those of Embodiments 1 to 3 to evaluate its amplification characteristics. As a result, the optical amplifier having any one of the fibers listed above as the amplification medium shows the NF of 5 dB or less.

Consequently, as explained above, Embodiments 1 to 4 allow the amplification of 1.55 μm band by the excitation to the $^4I_{11/2}$ level which enables them to achieve a low noise amplification whether an infrared-transparent fiber such as a fluoride one (which is regarded as an improper medium by persons skilled in the art) is used as a host of Er^{3+}. Hence, the optical amplifier having the characteristics of a flat gain with a wide amplification bandwidth and a low noise is obtained. The optical amplifier thus obtained can be applied in a communication system to increase a transmission volume thereof and to provide a diversification of the system configuration to achieve the wide dispersion of an optical communication, the substantial reduction in a manufacturing cost thereof, and so on.

(Embodiment 5)

An optical amplifier of the present embodiment is constructed so as to introduce at least one light as a third light corresponding to a difference between the $^4I_{13/2}$ level and the upper level into the Er^{3+}-doped fiber in addition of the pump light and the signal light.

Energy levels of Er^{3+} ions to be applied on the present embodiment will be described in detail with reference to Fig. 8. In this figure,(A) to (D) are illustrated for the purpose of explaining the different excitation ways of the Er^{3+} ions to the different energy levels. As shown in the figure, a pump excited state absorption (pump ESA) of the pump light by the transition from the $^4I_{11/2}$ level to the $^4F_{7/2}$ level occurs when the Er^{3+} ions are excited by the 0.98 μm pump light, resulting in the excitation to the $^4F_{7/2}$ level. Then a phonon emitted relaxation from the $^4F_{7/2}$ level to the $^4S_{3/2}$ level occurs. It means that a part of the Er^{3+} ions is pumped to the $^4S_{3/2}$ level. If an induced emission from the $^4S_{3/2}$ level to the $^4I_{13/2}$ level occurs by launching the light corresponding to the energy difference between the $^4S_{3/2}$ level and the $^4I_{13/2}$ level at a wavelength of 0.85 μm into the amplifier, a population density of the $^4S_{3/2}$ level can be reduced while a density of excited state of the $^4I_{13/2}$ level can be increased. Consequently, as shown in Fig. 8 (A), a gain efficiency of the optical amplifier can be improved as a result of increasing the density of inverted population in which the number of the Er^{3+} ions at the $^4I_{13/2}$ level (i.e., the higher energy level) exceed those at the $^4I_{15/2}$ level (i.e., the lower energy level). Energy levels to be excited by the pump ESA includes not only the $^4S_{3/2}$ level but also the $^4I_{9/2}$ level and the $^4F_{9/2}$ level as shown in Fig. 8 (C) and (B), respectively. In addition, the $^4I_{11/2}$ level to be directly excited at a wavelength of 0.98 μm has a large excited state density as shown in Fig. 8 (D). Therefore, an excited state density of the $^4I_{13/2}$ level can be increased by launching the light having the energy difference between the $^4I_{13/2}$ level and the$^4I_{9/2}$, $^4F_{9/2}$, or $^4I_{11/2}$ level at a wavelength of 1.65, 1.16, or 2.7 μm, respectively, just as in the case of launching the light at a wavelength of 0.85 μm into the fiber. In accordance with the present embodiment, therefore, the 0.98 μm pump light which is generally used in the conventional S-EDFA to attain a favorable amplification gain may be applied in the F-EDFA in order to realize lower noise amplification and higher amplification gain of the F-EDFA, compared with those of the conventional F-EDFA.

Fig. 9 is a block diagram to illustrate the construction of an optical amplifier of the present

Embodiment. In the figure, reference numerals 11 and 12 denote pump light sources, 13 and 14 denote optical couplers, 15 denotes an optical fiber doped with Er^{3+}, and 16 is an optical isolator. In addition, the arrows in the diagram indicate the direction of an input and an output of the signal, respectively. That is, an output of the signal (laser oscillation) is in the direction of the arrows. In this Embodiment, a semiconductor laser of 0.98 μm oscillation is used as the optical source 11, while a semiconductor laser of 0.85 μm oscillation is used as the optical source 12. Pump light from the light source 11 and pump light from the light source 12 are coupled together by the optical coupler 13. Then the coupled pump light from the optical coupler 13 is further coupled to an input signal in the direction of the arrow A by the optical coupler 14. Then output light from the optical coupler 14 is launched into the Er^{3+}-doped optical amplification fiber 15 of 10 m in length having a glass composition of ZrF_4-BaF_2-LaF_3-YF_3-AlF_3-PbF_2-LiF-HfF_4. In this embodiment, the fiber 15 also has a core of 2.5 μm in diameter being doped with 1,000 ppm Er^{3+} and a cut-off wavelength of 1 μm. A gain of 5 dB is obtained at a wavelength of 1.55 μm when 200 mW power pump light at a wavelength of 0.98 μm is only launched into the amplifier. In addition, a gain of 30 dB is obtained at a wavelength of 1.55 μm when 50 mW power pump light at a wavelength of 0.85 μm is only launched into the amplifier. In this case, the amplifier is further subjected to the NF measurement and it results in the NF of 4 dB.

A NF value of the optical amplifier using the Er^{3+}-doped fluoride fiber of the present embodiment by the pump light at a wavelength of 1.48 μm is measured and it results in the NF of 6 dB when the gain is 30 dB at a wavelength of 1.55 μm. Using the Er^{3+} -doped fluoride fiber of the present embodiment to obtain a value of the NF by an excitation at 1.48 μm wavelength, the NF of 6 dB is obtained when the gain is 30 dB at a wavelength of 1.55 μm. Consequently, the present embodiment attains the high gain of 30 dB which cannot be attained by the conventional optical amplifier with the excitation at a wavelength of 0.98 μm. In addition, the present embodiment attains about 2 dB reduction in the NF compared with that obtained by the excitation at a wavelength of 1.48 μm, so that the 0.97 μm pump Er^{3+} -doped fluoride fiber amplifier of the present embodiment shows substantially the same NF value as that obtained by the 0.98 μm pump S-EDFA.

(Embodiment 6)

In Embodiment 5, the incident light at a wavelength of 0.85 μm is used as one corresponding to the transition from the $^4S_{3/2}$ level to the $^4I_{13/2}$ level. In this embodiment, on the other hand, light at a wavelength of 2.7 μm as one corresponding to the transition from the $^4I_{11/2}$ level to the $^4I_{13/2}$ level is launched from a YAG laser 12 into the amplifier for the purpose of increasing a population of the $^4I_{13/2}$ level by directly decreasing a population of the $^4I_{11/2}$ level excited at a wavelength of 0.98 μm as a result of an induced emission caused by the transition from the $^4I_{11/2}$ level to the $^4I_{13/2}$ level. In this case, comparing with those of only the 0.98 μm pump light, an increase in the gain at a wavelength of 1.55 μm and a decrease in the NF are observed. Besides, the amplification characteristics of the amplifier can be improved by launching light at a wavelength of 1.16 μm into the fiber by means of a semiconductor laser as light source 12.

(Embodiment 7)

In this embodiment, a light at a wavelength of 1.65 μm from a light source (i.e., a semiconductor laser) 12 is used as one corresponding to the transition from the $^4I_{9/2}$ level to the $^4I_{13/2}$ level. In this case, comparing with those of only the 0.98 μm excitation, an increase in the gain at a wavelength of 1.55 μm and a decrease in the NF are observed.

In Embodiment 6 and Embodiment 7, as described above, the light source 12 emits the incident light at a wavelength of 0.85, 2.7, 1.16, or 1.65 μm. It is noted that there is a width of the transition energy from the $^4S_{3/2}$, $^4I_{9/2}$, or $^4I_{11/2}$ level to the $^4I_{13/2}$ level. Thus, the incident light in the energy width launched from the light source 12 can be effective.

The available light source 12 may be not only selected from semiconductor lasers and solid state lasers such as an Er:YAG laser but also selected from fiber lasers such as an Er^{3+}-doped fluoride fiber laser as a light source of emitting light at a wavelength of 2.7 µm.

In addition to the above three energy levels $^4S_{3/2}$, $^4I_{9/2}$, and $^4I_{11/2}$, there are other energy levels (not shown) higher than the $^4I_{13/2}$ level. Thus, it is possible to improve the amplification characteristics of the amplifier by incident light having an energy corresponding to the energy difference between the higher energy level and the $^4I_{13/2}$ level.

Furthermore, the light for the transition from the higher energy level to the $^4I_{13/2}$ level is not limited to one type. A plurality of light beams at different wavelengths may be launched into the amplifier simultaneously with the pump light. The pump light may be responsible for the direct excitation to an energy level higher than the $^4I_{9/2}$ level, for example the direct excitation from the $^4I_{9/2}$ level to the $^4S_{3/2}$ level.

(Embodiment 8)

In Embodiments 5 to 7 described above, the Er^{3+} doped ZrF_4-based fluoride fiber is used as the amplification medium. It is also known that a gain of at a wavelength of 1.55 µm is hardly obtainable when the 0.98 µm pump (the excitation to the $^4I_{11/2}$ level) is applied in an amplifier where one of an Er^{3+}-doped ZrF_4-AlF_2 based fluoride fiber, an Er^{3+} -doped InF_3 based fiber, an Er^{3+}-doped chalcogenide glass fiber, and an Er^{3+}-doped telluride glass fiber is provided as the amplification medium. In this embodiment, therefore, an effective use of any one of those amplification media in which a material with a low phonon energy is used as a host can be attained in accordance with the present invention.

Also, an excitation to an energy level higher than the $^4I_{11/2}$ is not limited to the 0.98 μm pump. This excitation can be also attained by the 0.8 μm pump (the excitation to the $^4F_{9/2}$ level). In this case, an increase in the gain at a wavelength of 1.55 μm and a decrease in the NF are obtained by launching the 0.8 μm pump light into the fiber simultaneously with additional incident light (i.e., light at a wavelength of 0.8 μm) having an energy corresponding to the transition from an energy level higher than the $^4I_{13/2}$ level to the $^4I_{13/2}$ level.

(Embodiment 9)

Fig. 10 is a schematic block diagram of a laser as one of the preferred embodiments of the present invention. In the figure, reference numerals 11 and 12 denote light sources, 13 denotes an optical coupler, 17 and 17' denote resonance mirrors, and 18 denotes a crystal as an amplification medium. In addition, an arrow indicates the direction of a signal output. A crystal to be used as the amplification medium is one of Er^{3+}-doped halide crystals such as LaF^3, BaF^2, LaC^{13}, and YF^3. In this embodiment, the characteristics of 1.5 μm amplification and laser oscillation of the laser using the halide crystal are investigated. As a result, an increase in the gain and an increase in the efficiency of laser oscillation are obtained when the light for the induced emission from an higher energy level to the $^4I_{13/2}$ level is launched in the fiber simultaneously with pump light at the wavelengths of 0.8 and 0.98 µm.

(Embodiment 10)

Fig. 11 is a schematic block diagram of a laser as another preferred embodiment of the present invention. In the figure, reference numerals 11 and 12 denote light sources, 13 denotes an optical coupler, 15 denotes an Er^{3+}-doped optical fiber 15 for the amplification, and 17 and 17′ denote resonance mirrors. In addition, an arrow indicates the direction of an output (laser oscillation). The Er^{3+}-doped optical fiber is prepared so as to include a glass composition of ZrF_4-BaF_2-LaF_3-YF_3-AlF_3-PbF_2-LiF-HfF_4 and is incorporated in the laser shown in Fig. 11, resulting in a laser oscillation at a wavelength of 1.5 µm. In this embodiment, light sources of 0.98 and 0.85 µm wavelengths were used as the pump light sources 11, 12. When a pass of light from the light source of 0.85 µm wavelength is blocked, the strength of the laser oscillation is remarkably decreased.

(Embodiment 11)

Fig. 12 is a schematic block diagram of a laser as another preferred embodiment of the present invention. In the figure, a reference numeral 11 denotes a light source consisting of a semiconductor laser of 0.98 μm oscillation, 12 denotes a light source consisting of a semiconductor laser of 0.85 μm oscillation, 13, 14 and 14' denote optical couplers, and 15 denotes an Er^{3+}-doped optical amplifier for the amplification.

After coupling the pump light from the light sources 11 and 12 together by the optical coupler 13, output pump light produced from the optical coupler 13 is coupled to an incident signal light provided from the direction indicated by an arrow A in the figure by the optical coupler 14. Furthermore, the pump light from the light source 19 is launched into the Er^{3+}-doped optical fiber 15 through the optical coupler 14'.

The Er^{3+}-doped optical fiber 15 provided as an amplification medium in the present embodiment is prepared so as to have the same glass composition as that of Embodiment 10, i.e., ZrF_4-BaF_2-LaF_3-YF_3-AlF_3-PbF_2-LiF-HfF_4. In addition, the fiber 15 is of an Er^{3+}-doped concentration of 1,000 ppm, a length of 10 m, a high relative refractive-index difference of 2.5 %, and a cut-off wavelength of 1 μm. When the pump light at a wavelength of 0.98 μm is only launched into the fiber for 200 mW, the gain at a wavelength of 1.5 μm is 5 dB. When the pump light at a wavelength of 0.85 μm is launched into the fiber for 30 mW, the gain at a wavelength of 1.55 μm is 15dB. When an additional pump light at a wavelength of

1.48 µm is launched into the fiber in addition to the pump light of 0.85 µm wavelength, the gain at a wavelength of 1.55 µm is 40 dB. In this case, a measured value of the NF of the amplifier is 3.8 dB.

Furthermore, the NF of the amplifier comprising the Er^{3+}-doped optical fiber of the present embodiment is also measured by an excitation at a wavelength of 1.48 µm. The NF of 6 dB is obtained when the gain at a wavelength of 1.55 µm is 40 dB. Consequently, a configuration of the amplifier of the present embodiment enables it to provide an amplifier having an excellent gain of 40 dB which has not been attained by the 0.98 µm pump conventional amplifier, together with a decrease in the NF, i.e., 2 dB or less dropped from that of the 1.48 µm pump. We confirm that the NF of the amplifier of the present Embodiment is substantially the same level as that of the 0.98 µm pump S-EDFA.

(Embodiment 12)

In Embodiment 11, the light of 0.85 µm wavelength is used as the light corresponding to the transition from the $^4S_{3/2}$ level to the $^4I_{13/2}$ level. In this embodiment, on the other hand, the light corresponding to the transition from the $^4I_{11/2}$ level to the $^4I_{13/2}$ level is launched into the fiber from the light source 12 (i.e., an Er:YAG laser of 2.7 µm oscillation is used as the light source). In this case, an increase in the gain at a wavelength of 1.55 µm and a decrease in the NF of the amplifier are observed.

The amplification characteristics of the amplifier is also improved by launching the incident light at a wavelength of 1.16 µm into the amplification medium from a semiconductor being provided as the light source 12.

(Embodiment 13)

In Embodiment 11, light at a wavelength of 0.85 µm corresponding to the transition from the $^4S_{3/2}$ level to the $^4I_{11/2}$ level is launched into the amplifier. In Embodiment 12, furthermore, light corresponding to the transition from the $^4I_{11/2}$ level to the $^4I_{13/2}$ level is launched into the amplifier from the light source 12. In the present embodiment, on the other hand, light at a wavelength of 1.65 µm corresponding to the transition from the $^4I_{9/2}$ level to the $^4I_{13/2}$ level is launched into the amplifier from the light source 12 (semiconductor laser). In this case, an increase in the gain at a wavelength of 1.55 µm and a decrease in the NF are observed, compared with those of the 0.98 µm excitation by itself.

In Embodiments 11 to 13 as described above, the light source 12 emits the incident light at a wavelength of 0.85, 2.7, 1.16, or 1.65 µm. It is noted that there is a width of the transition energy from the $^4S_{3/2}$, $^4I_{9/2}$, or $^4F_{9/2}$, or $^4I_{11/2}$ level to the $^4I_{13/2}$ level. Thus, the incident light in the energy width launched from the light source 12 can be effective.

The available light source 12 may be not only selected from semiconductor lasers and solid state lasers such as an Er:YAG laser but also selected from fiber lasers such as an Er^{3+}-doped fluoride fiber laser as a light source of emitting a light a wavelength of 2.7 µm.

In addition to the above three energy levels: $^4S_{3/2}$, $^4I_{9/2}$, and $^4I_{11/2}$, there are other energy levels (not shown) higher than the $^4I_{13/2}$ level. Thus, it is possible to improve the amplification characteristics of the amplifier by incident light having an energy corresponding to the energy difference between the higher energy level and the $^4I_{13/2}$ level.

Furthermore, the number of lights for the transition from the higher energy level to the $^4I_{13/2}$ level is not limited to one type. A plurality of lights at different wavelengths may be launched into the amplifier simultaneously with the pump light. The pump light may be for the direct excitation to an energy level higher than the $^4I_{9/2}$ level, for example the $^4F_{9/2}$ level and the $^4S_{3/2}$ level.

(Embodiment 14)

In the present embodiment, as shown in Fig. 9, an optical amplifier having two light sources 11 and 12 is prepared, where the light source 11 is a semiconductor laser that oscillates at a wavelength of 0.97 µm and the light source 12 is a semiconductor laser that oscillates at a wavelength of 0.855 µm. After coupling pump light from the light sources 11 and 12 by an optical coupler 13, output pump light from the coupler 13 passes through another optical coupler 14 where it is further coupled to incident signal light provided from an optical isolator (not shown) in the direction indicated by an arrow A in the figure. Then output pump light from the optical coupler 14 is launched into an Er^{3+}-doped optical fiber 15 for the amplification of the pump light.

The above Er^{3+} -doped optical fiber 15 has a glass composition of ZrF_4-BaF_3-LaF_3-YF_3-AlF_3-PbF_2-LiF-NaF-HfF_4 and its core is doped with Er^{3+} in an amount equal to 1,000 ppm. In addition, the fiber 10 is prepared as one having a length of 10 m, a difference in refractive indexes between the core portion and the cladding portion of 2.5 %, and a cut-off wavelength of 1 μm. In this embodiment, furthermore, a gain of 40 dB can be attained when additional light at a wavelength of 0.855 μm with a power of 10 mW is simultaneously launched into the fiber in addition to the 0.97 μm pump light. At this time, a NF of 3.8 dB is obtained.

The amplifier system of the present embodiment uses the process of exciting to the $^4I_{13/2}$ level including the steps of: a two-stage excitation in which the $^4I_{15/2}$ level is excited to the $^4I_{11/2}$ level and then the $^4I_{11/2}$ level is excited to the $^4F_{7/2}$ level; and an induced transition from the $^4S_{3/2}$ level to the $^4I_{13/2}$ level. Therefore appropriate pump wavelengths should be selected for effectively performing the above two-stage excitation to attain the excitation to the $^4I_{13/2}$ level.

Fig. 13 shows the changes in an excitation density of the $^4S_{3/2}$ by shifting the pump wavelength. The results shown in the figure are obtained by the changes in an emitting strength of the amplifier at the transition from the $^4S_{3/2}$ level to the $^4I_{13/2}$ level. As shown in Fig. 13, the Er^{3+}-doped fluoride fiber can be excited effectively to the $^4S_{3/2}$ level at a pump wavelength in the range of 960 nm to 980 nm, and especially a high efficient excitation to the $^4S_{3/2}$ level can be attained at a pump wavelength of approximately 969 nm.

For the light responsible for an induced emission from the $^4S_{3/2}$ level to the $^4I_{13/2}$ level, a pump wavelength thereof may be selected from 0.82 μm to 0.88 μm because of an emitted cross section of the transition from the $^4S_{3/2}$ level to the $^4I_{13/2}$ level in existence as shown Fig. 14. In the wavelength region of 0.84 μm to 0.88 μm, the induced emission cross section is greater than the absorption cross section, so that it is possible to attain an induced emission from the $^4S_{3/2}$ level to the $^4I_{13/2}$ level with efficiency using the light at a wavelength in the above region.

(Embodiment 15)

In this embodiment, as shown in Fig. 12, an Er^{3+}-doped fluoride fiber amplifier (F-EDFA) is prepared by installing a third light source 19 in addition to the light sources 11, 12 used in the F-EDFA of Embodiment 5 (see Fig. 9). In addition, an additional optical coupler 14′ is installed instead of the optical isolator 16 so as to be connected to the third light source 19. Thus another pumping light can be launched in the Er^{3+}-doped fiber 15 through the optical coupler 14' in the downstream part of the F-EDFA. In this embodiment, furthermore, the light at a pump wavelength of 1.48 µm is used. Therefore, the F-EDFA of the present embodiment is configured to incorporate an additional excitation at a wavelength of 1.48 µm for performing a direct excitation to the $^4I_{13/2}$ level to attain a low noise figure (NF) and a high-output whether a large signal is launched into the F-EDFA.

In the case of using an Er^{3+}-doped silica fiber, an amplifier (i.e., an Er^{3+}-doped silica fiber amplifier: S-EDFA) having the properties of producing a high-output and a low noise figure (NF) can be constructed by incorporating the means of launching a pump light at a wavelength of 0.98 µm from the upstream to the fiber and the means of launching pump light at a wavelength of 1.48 µm from the downstream to the fiber. In the case of using the Er^{3+}-doped fluoride fiber, on the other hand, two different pump light beams at wavelengths of 0.97 and 0.855 µm are simultaneously launched in the fiber so as to avoid a serious degradation of an efficiency of exciting to the $^4I_{13/2}$ level to be caused by launching only the pump light at a wavelength of 0.97 µm into the fiber.

An amplification gain of 15 dB or more and a NF of 5 dB or less are obtained at a wavelength in the above wavelength region by performing the excitation when a pump power of the 0.97 µm pump light launched into the fiber is

100 mW and a pump power of the 0.85 μm pump light launched into the fiber is 20 mW. The signal light input is performed through an optical amplifier (not shown in Fig. 12).

Therefore, the excitation method in accordance with the present embodiment improves the amplification characteristics of the F-EDFA, so that it is effective to construct an amplifier having the properties of producing a high-output with a low noise.

(Embodiment 16)

Fig. 15 is a perspective diagram of a main constructed portion of an optical amplifier in the type of an optical waveguide in accordance with the present invention. In the figure, a reference numeral 110 denotes a core portion, 111 denotes a cladding portion, and 112 denotes a substrate portion. In this embodiment, the core and cladding portions are made of a fluoride glass. In addition, the core portion 110 is doped with 10 % by 20 weight of Er^{3+}.

In this embodiment, composite light consisting of the light at a wavelength of 1.48 μm and the light at a wavelength of 0.86 μm is launched into the core portion 110.

If the Er^{3+}-doped concentration in the core portion 110 is increased, an energy movement in the Er^{3+} ions is caused by electric dipole interactions among them as a result of a decrease in the distance among the Er^{3+} ions in the fluoride glass proportionate to the above increase.

Fig. 16 shows energy levels of Er^{3+} , for illustrating excitation states of the Er^{3+} in consideration of interactions among the Er^{3+} ions. If the pump light at a wavelength of 1.48 µm is launched into the core portion for the excitation to the $^4I_{13/2}$ level, a cooperative up-conversion occurs by the transition from the $^4I_{13/2}$ level to the $^4I_{15/2}$ level and the excitation from the $^4I_{13/2}$ level to the $^4I_{9/2}$ level. After the excitation to the $^4I_{9/2}$ level, a relaxation from the $^4I_{9/2}$ level to the $^4I_{11/2}$ level occurs by a multiple phonon emission, resulting in the excitation to the $^4I_{11/2}$ level. Then, an excited state density of the $^4I_{11/2}$ level is increased and subsequently a cooperative up-conversion occurs by the transition from the $^4I_{11/2}$ level to the $^4I_{15/2}$ level and the excitation from the $^4I_{11/2}$ level to the $^4F_{7/2}$ level, resulting in the excitation to the $^4F_{7/2}$ level. Finally, the excitation to the energy levels such as $^4S_{3/2}$ and $^4F_{7/2}$, which are not directly excited by the pump light at a wavelength of 1.48 µm, can be attained. Consequently, an efficiency of the excitation to the $^4I_{13/2}$ level is decreased, so that the possibility of causing an optical amplification at a wavelength of 1.55 µm substantially disappears. In accordance with the present embodiment, the amplifier is constructed so as to increase the excited state density of the $^4I_{13/2}$ level by causing an induced emission from the $^4S_{3/2}$ level to the $^4I_{11/2}$ level. As a consequence, an amplification gain of

30 dB is obtained at a wavelength of 1.55 μm when the 1.48 μm pump power is 150 mW and the 0.86 μm pump power is 20 mW. If the 1.48 μm pumping power is used, an appropriate amplification gain cannot be obtained. Thus an incident light at a wavelength of 0.86 μm shows a significant effect on the amplification efficiency.

In this embodiment, furthermore, the light that causes an induced emission from the $^4S_{3/2}$ level to the $^4I_{13/2}$ is launched in the amplifier. As described above, the energy levels of $^4F_{9/2}$, $^4I_{9/2}$, and $^4I_{11/2}$ are also excited, so that an improvement in the amplification efficiency is attained by launching the light that causes an induced emission from any of those energy levels to the $^4I_{13/2}$ level into the amplifier in addition to the incident pumping light at a wavelength of 1.48 μm.

(Embodiment 17)

An amplifier in the type of an optical waveguide has the same configuration as that of Embodiment 16 as shown in Fig. 15 except as follows. That is, the core and cladding portions are made of a telluride glass. In addition, the core portion is doped with 20 % by weight of Er^{3+}. Then, operating characteristics of the amplifier having the above structure are studied and the following results are obtained. In the case of using a telluride glass as a material of the optical waveguide, the energy levels of $^4S_{3/2}$, $^4F_{9/2}$, $^4I_{9/2}$, $^4I_{11/2}$, and the like are excited through the interactions among the Er^{3+} ions when the Er^{3+} concentration is high. Therefore, the excitation to the $^4I_{13/2}$ level can be effectively performed as a result of the induced emission from any of those energy levels to the $^4I_{13/2}$ level by launching the light corresponding to the former level into the amplifier. In this embodiment, light at a wavelength of 0.875 μm is launched simultaneously with the 1.48 μm pump light. As a consequence, an amplification gain of 30 dB is obtained at a wavelength of 1.55 μm when the 1.48 μm pump power is 150 mW and the 0.875 μm pump power is 20 mW. If the 1.48 μm pump power is used alone, an appropriate amplification gain cannot be obtained. Thus an incident light at a wavelength of 0.875 μm shows a significant effect on the amplification efficiency.

In this embodiment, the 1.48 μm pump light and the 0.875 μm pump light are launched into the optical waveguide from the same direction. However, they can be launched into the optical waveguide from the opposite directions.

(Embodiment 18)

An optical amplifier in the type of an optical waveguide has the same construction as that of Embodiments 16 and 17 shown in Fig. 15 except that the core and cladding portions are made of a silica glass and also the core portion is doped with 1 % by weight of Er^{3+}.

Operating characteristics of the amplifier having the above structure are studied and the following results are obtained. In the case of using a silica glass as a material of the optical waveguide, the energy levels of $^4S_{3/2}$, $^4F_{9/2}$, $^4I_{9/2}$, $^4I_{11/2}$, and the like are excited through the interactions among the Er^{3+} ions when the Er^{3+} concentration is high. Therefore, the excitation to the $^4I_{13/2}$ level can be effectively performed as a result of the induced emission from any of those energy levels to the $^4I_{13/2}$ level by launching the light corresponding to the former level into the amplifier. In this embodiment, light at a wavelength of 0.87 µm is launched simultaneously with the 1.48 µm pump light. As a consequence, an amplification gain of 30 dB is obtained at a wavelength of 1.55 µm when the 1.48 µm pump power is 150 mW and the 0.87 µm pump power is 20 mW. If the 1.48 µm pump power is used alone, an appropriate amplification gain cannot be obtained. Thus an incident light at a wavelength of 0.87 µm shows a significant effect on the amplification efficiency.

As described above, the optical amplifiers and the lasers of Embodiments 5 to 18 are characterized by having first and second light sources at different wavelengths for the pump light. In addition, the first light source is responsible for emitting light at a wavelength corresponding to the energy difference between the $^4I_{13/2}$ level of erbium and an energy level higher than the $^4I_{13/2}$ level. Therefore, as explained above, it is possible to attain the amplification of a 1.55 µm band by the 0.98 µm pump which enables it to achieve a low noise amplification whether an infrared-transparent fiber such as a fluoride one (which is regarded as an improper medium by persons skilled in the art) is used as a host of Er^{3+}. Hence, the optical amplifier having the characteristics of a flat gain with a wide amplification bandwidth and a low noise is obtained. The optical amplifier thus obtained can be applied in a communication system to increase a transmission volume thereof and to provide a diversification of the system configuration to achieve the wide dispersion of an optical communication, the substantial reduction in a manufacturing cost thereof, and so on.

What is claimed is:

1. A method for amplifying an optical signal at a wavelength band of 1.5 μm that uses an optical amplification medium doped with Er^{3+} ions, comprising a step of exciting said Er^{3+} ions by light of at least one wavelength in a range of 0.96 μm up to but not including 0.98 μm, where said optical amplification medium is selected from a group of a fluoride glass, a chalcogenide glass, a telluride glass, a halide crystal, and a lead oxide based glass.

2. A method as claimed in Claim 1, wherein

said optical amplification medium is in a shape of a fiber.

3. An optical amplifier for amplifying an optical signal at a wavelength band of 1.5 μm having an optical amplification medium doped with Er^{3+} ions, wherein said optical amplification medium is selected from a group of a fluoride glass, a chalcogenide glass, a telluride glass, a halide crystal, and a lead oxide based glass, and

said ER^{3+} ions are excited by light of at least one wavelength in a range of 0.96 μm up to but not including 0.98 μm.

4. An optical amplifier as claimed in Claim 3, wherein

said optical amplification medium is in a shape of a fiber.

5. An optical amplifier as claimed In Claim 3, further comprising:

a light source for an excitation to $^4I_{13/2}$ level.

6. An optical amplification method that uses an optical amplifier having: an optical amplification medium doped with Er^{3+} ions and selected from a group of a fluoride glass, a chalcogenide glass, a telluride glass, a halide crystal, and a

lead oxide based glass; a light source for exciting said Er^{3+} ions with an oscillation wavelength in a range of 0.96 μm up to but not including 0.98 μm; and a light source for an excitation to $^4I_{13/2}$ level, comprising steps of: launching pump light, which is emitted in the same direction as that of launching a signal light into said optical amplification medium from said light source for exciting said Er^{3+} ions with an oscillation wavelength in a range of 0.96 μm up to but not including 0.98 μm, into said optical amplification medium; and

launching light, which is emitted in an opposite direction of said pump light, from said light source for an excitation to $^4I_{13/2}$ level into said optical amplification medium.

7. An optical amplification method as claimed in Claim 6, wherein

said optical amplification medium is in a shape of a fiber.

8. A laser having an optical amplification medium doped with Er^{3+} ions and a pump light source for an excitation of said optical amplification medium and using an induced emission of Er^{3+} ions from $^4I_{11/2}$ level to $^4I_{15/2}$ level, wherein

said pump light source includes at least a first light source and a second light source, which emit light at different wavelengths, and

said first light source is provided as a light source for emitting light at a wavelength

corresponding to an energy difference between $^4I_{13/2}$ level of said Er^{3+} ions and an energy level higher than said $^4I_{13/2}$ level to promote an induced relaxation to $^4I_{13/2}$ level of said Er^{3+} ions.

9. A laser as claimed in Claim 8, wherein

said first light source is provided as a light source for emitting light at a wavelength

corresponding to an energy difference between $^4I_{13/2}$ level and one energy level selected from a group of $^4I_{11/2}$ level, $^4I_{9/2}$ level, $^4F_{9/2}$ level, and $^4S_{3/2}$ level of said Er^{3+} ions.

10. A laser as claimed in Claim 8, wherein

said second light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and one energy level selected from a group of $^4I_{11/2}$ level and $^4F_{9/2}$ level of said Er^{3+}, ions.

11. A laser as claimed in Claim 8, further comprising a third light source, wherein

said first light source is provided as a light source f or emitting light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level and $^4S_{3/2}$, level of said Er^{3+} ions; and

said second light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4\ _{11/2}$ level of said Er^{3+} ions; and

said third light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{13/2}$ level of said Er^{3+} ions.

12. A laser as claimed in Claim 8, wherein

said first light source is provided as a light source for emitting light at a wavelength of 0.82 µm to 0.88 µm; and

said second light source is provided as a light source for emitting light at a wavelength of 0.96 µm up to but not including 0.98 µm.

13. A laser as claimed in Claim 8, wherein

said optical amplification medium doped with Er^{3+} ions is selected from a group of a fluoride fiber doped with Er^{3+} ions, a chalcogenide fiber doped with ER^{3+} ions, a telluride fiber doped with Er^{3+} ions, and a halide crystal doped with Er^{3+} ions.

14. An optical amplifier at least comprising:

an optical amplification medium doped with Er^{3+} ions;

means for inducing and isolating signal light at a wavelength of 1.5 µm into said optical amplification medium; and

a pump light source for the exaltation of said optical amplification medium, wherein

said pump light source includes at least a first light source and a second light source, which emit light at different wavelengths, and

said first light source is provided as a light source for emitting light at a wavelength

corresponding to an energy difference between the $^4I_{13/2}$ level of said Er^{3+} ions and an energy level higher than said $^4I_{13/2}$ level to promote an induced relaxation to $^4I_{13/2}$ level of said Er^{3+} ions.

15. An optical amplifier as claimed in Claim 14, wherein

said first light source is provided as a light source for emitting light at a wavelength

corresponding to an energy difference between $^4I_{13/2}$ level and one energy level selected from a group of $^4I_{11/2}$ level, $^4I_{9/2}$ level, $^4F_{9/2}$ level, and $^4S_{3/2}$, level of said Er^{3+} ions.

16. An optical amplifier as claimed in Claim 14, wherein

said second light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and one energy level selected from a group of $^4I_{11/2}$ level and $^4F_{9/2}$ level of said Er^{3+} ions.

17. An optical amplifier as claimed in Claim 14, further comprising a third light source, wherein

said first light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{13/2}$ level and $^4S_{3/2}$ level of said Er^{3+} ions to promote an induced relaxation to $^4I_{13/2}$ level Er^{3+} ions.

said second light source is provided as a light source for emitting light at a wavelength

corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{11/2}$ level of said Er^{3+} ions; and

said third light source is provided as a light source for emitting light at a wavelength

corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{13/2}$ level of said Er^{3+} ions.

18. An optical amplifier as claimed in Claim 14, wherein

said first light source is provided as a light source for emitting light at a wavelength of 0.82 pm

to 0.88 μm; and

said second light source is provided as a light source for emitting light at a wavelength of 0.96 μm up to but not including 0.98 μm.

19. An optical amplifier as claimed in Claim 14, wherein

said second light source is provided as a light source for emitting light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level of said Er^{3+} ions.

20. An optical amplifier as claimed in Claim 14, wherein

said optical amplification medium doped with Er^{3+} ions is selected from a group of a fluoride fiber doped with Er^{3+} ions, a chalcogenide fiber doped with Er^{3+} ions, a telluride fiber doped with Er^{3+} ions, and a halide crystal doped with Er^{3+} ions.

21. An optical amplifier that uses Er^{3+} ions as amplification active elements, comprising:

means for launching at least one light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{11/2}$ level of said Er^{3+} ions, at least one light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and an energy level higher than said $^4I_{11/2}$ level of said Er^{3+} ions, and at least one light to be amplified by an induced emission transition from $^4I_{13/2}$ level to $^4I_{15/2}$ level into an amplification medium doped with said Er^{3+} ions from the same direction.

22. An optical amplifier as claimed in claim 21, wherein

light at a wavelength different from said light to be amplified and corresponding to an energy difference between the $^4I_{13/2}$ level and $^4I_{15/2}$ level of said Er^{3+} ions is launched into said amplification medium from a direction different from said same direction.

23. An optical amplification method that uses Er^{3+} ions as amplification active elements, comprising a step of launching light at a wavelength corresponding to an energy difference between $^4I_{15/2}$ level and $^4I_{11/2}$ level of said Er^{3+} ions, light at a wavelength corresponding to an energy difference between $^4S_{3/2}$ level and $^4I_{13/2}$ level of said Er^{3+} ions to promote an induced relaxation to $^4I_{13/2}$ level of said Er^{3+} ions, and light to be

amplified by an induced emission transition from $^4I_{13/2}$ level to $^4I_{15/2}$ level into an amplification medium doped with said Er^{3+} ions from the same direction.

24. An optical amplification method as claimed in Claim 23, wherein

light at a wavelength different from said light to be amplified and corresponding to an energy difference between the $^4I_{13/2}$ level and $^4I_{15/2}$ level of said Er^{3+} ions is launched into said amplification medium from a direction different from said same direction.

25. An optical amplification method that uses Er^{3+} ions as amplification active elements, comprising a step of launching light at a wavelength of 0.82 µm to 0.88 µm to promote an induced relaxation from $^4S_{3/2}$ level to $^4I_{13/2}$ level of said Er^{3+} ions, light at a wavelength of 0.96 µm up to but not including 0.98 µm, and light to be amplified by an induced emission transition from $^4I_{13/2}$ level to $^4I_{15/2}$ level into an amplification medium doped with said Er^{3+} ions from the same direction.

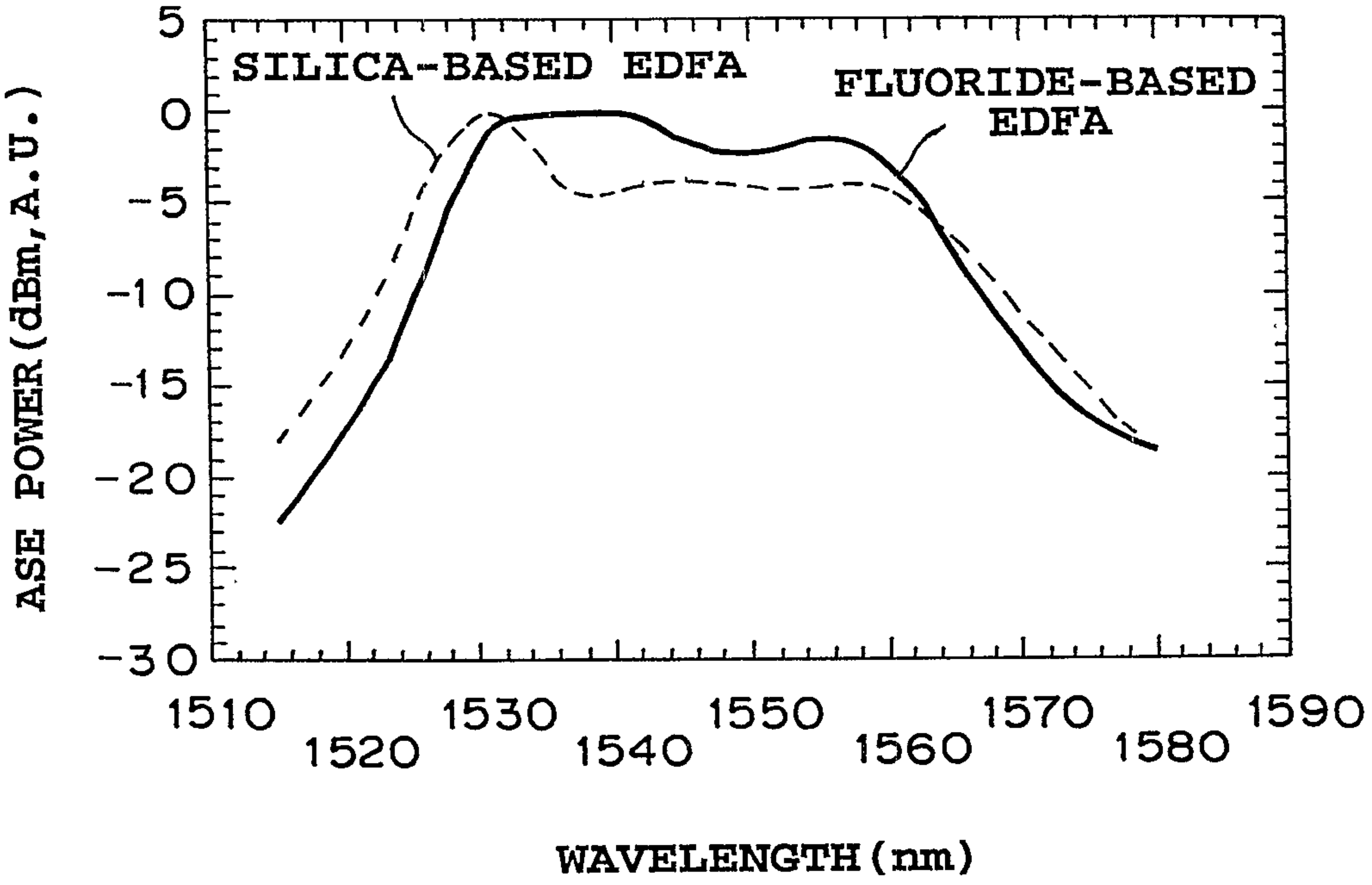

SILICA-BASED EDFA
FLUORIDE-BASED EDFA
ASE POWER (dBm, A.U.)
5
0
-5
-10
-15
-20
-25
-30
1510
1520
1530
1540
1550
1560
1570
1580
1590
WAVELENGTH (nm)

FIG.1

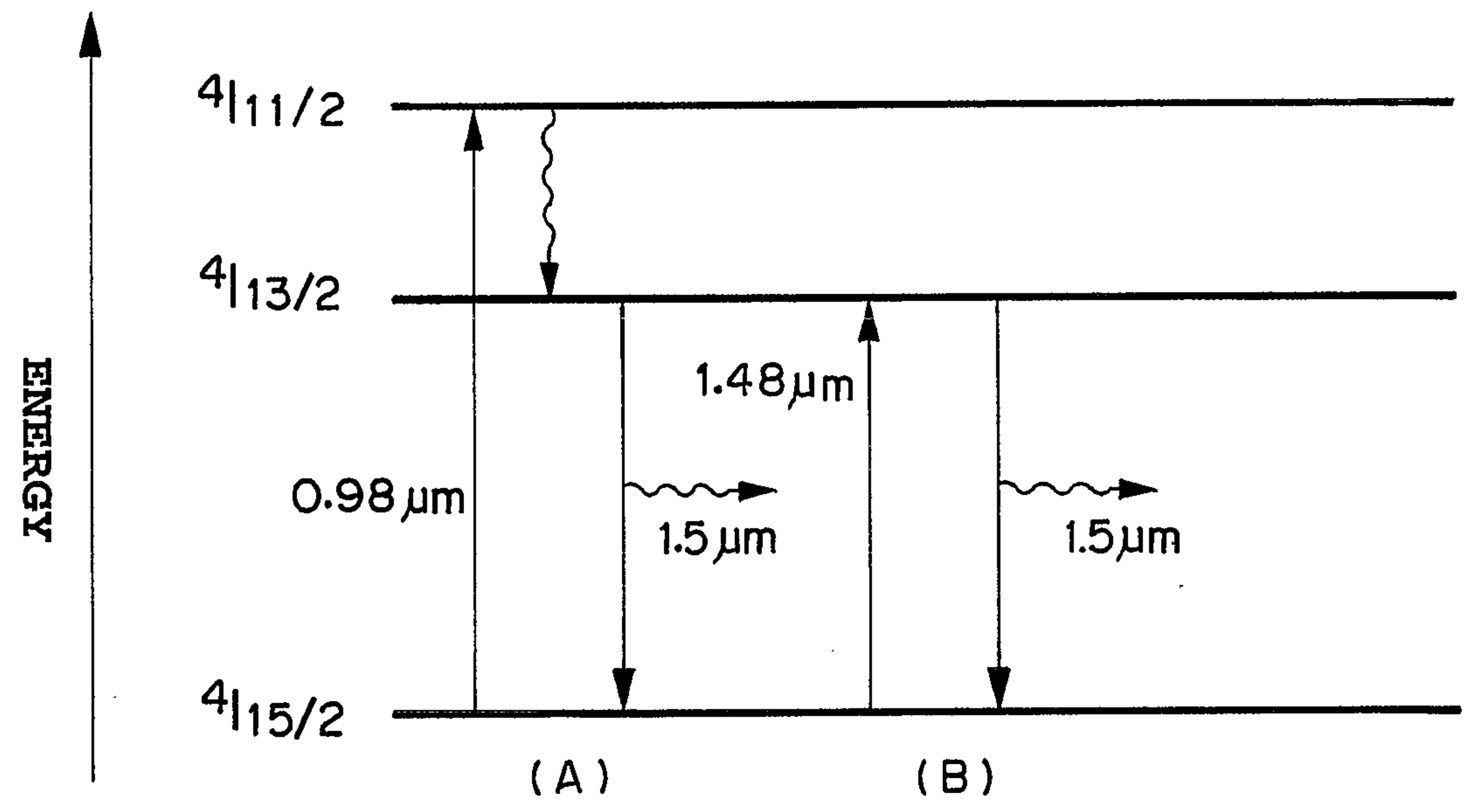


FIG.2
(PRIOR ART)

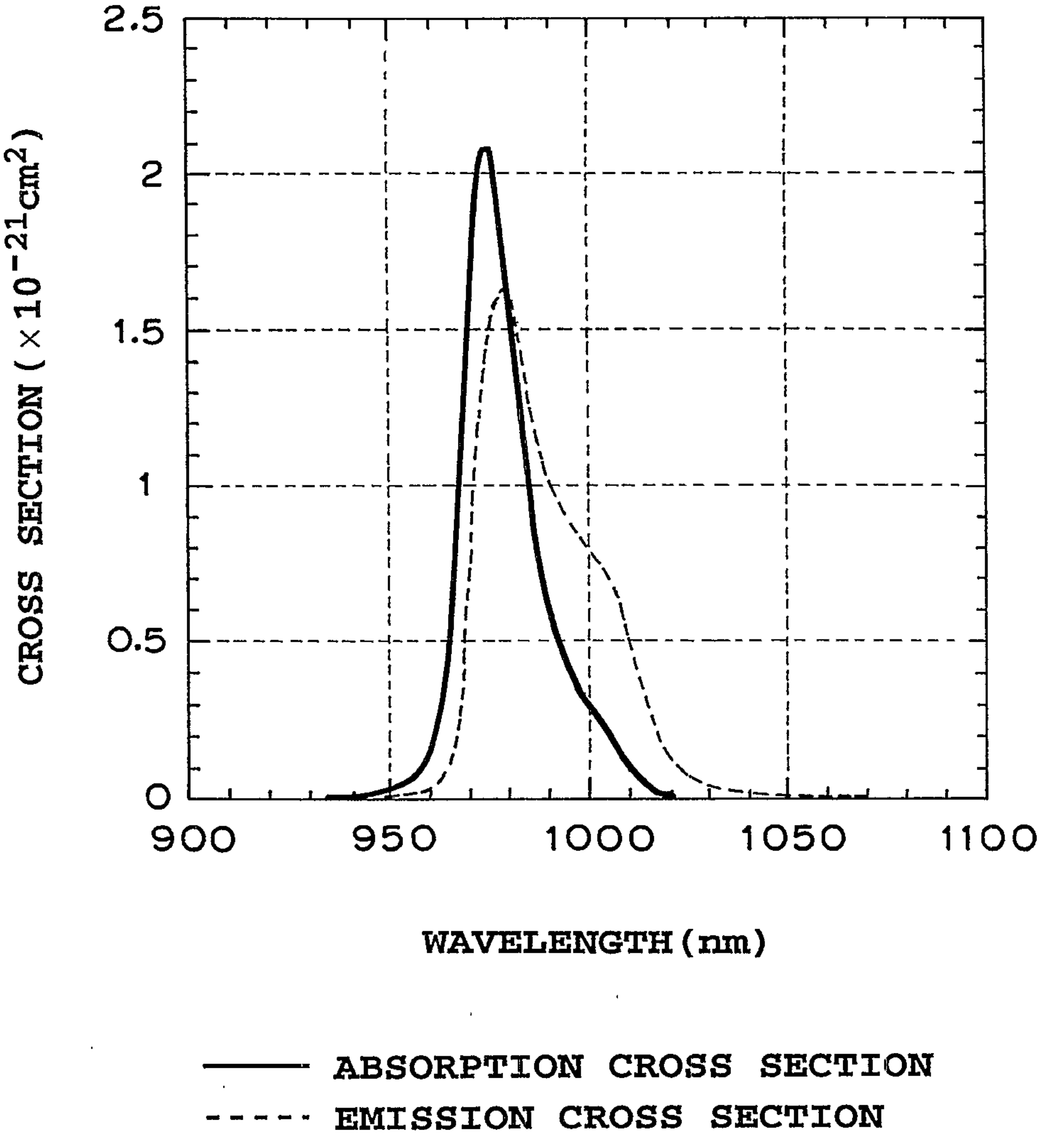

2.5
2
1.5
1
0.5
0
900
950
1000
1050
1100
CROSS SECTION (× 10⁻²¹cm²)
WAVELENGTH (nm)
ABSORPTION CROSS SECTION
EMISSION CROSS SECTION

FIG. 3

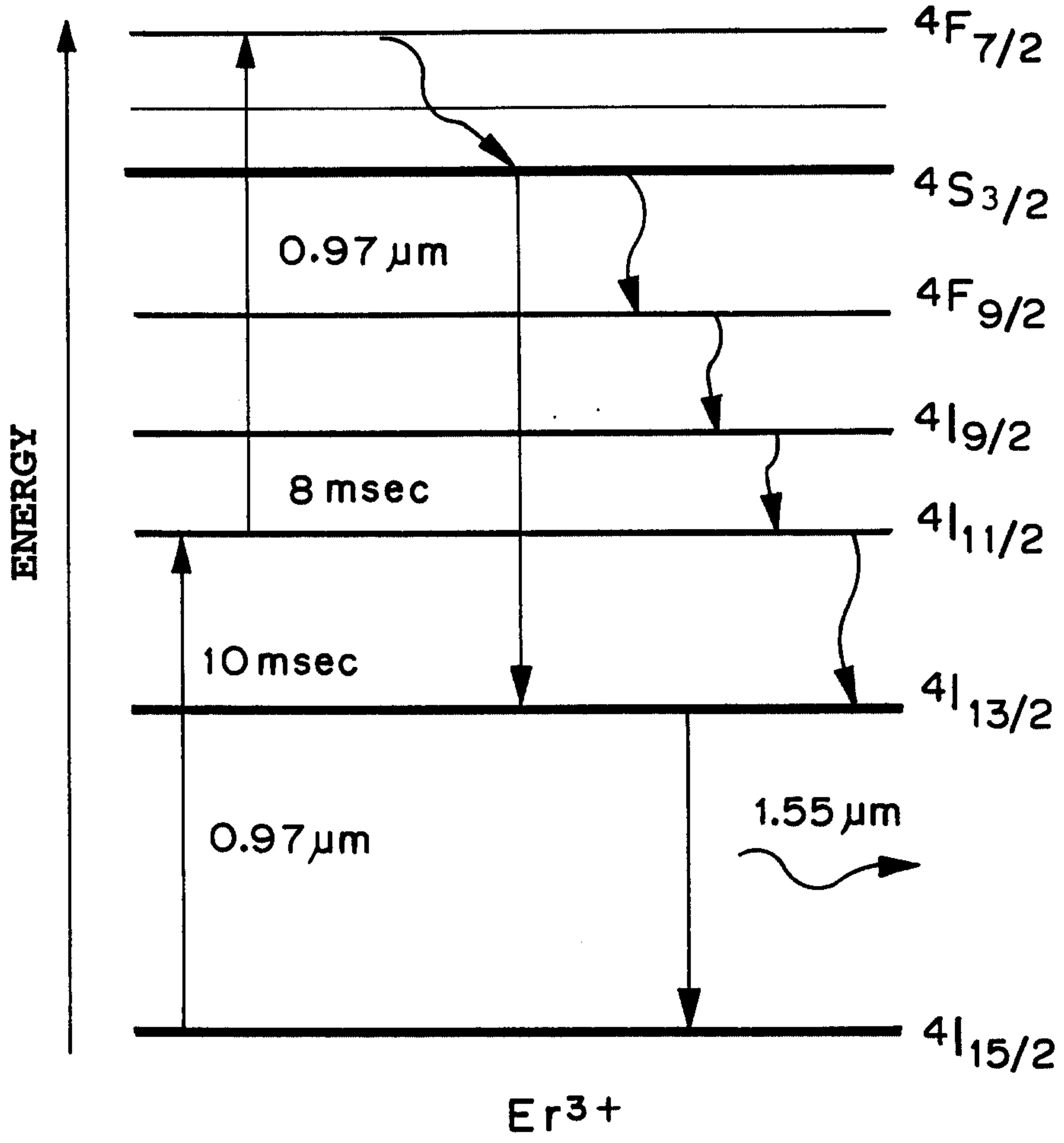

$^4F_{7/2}$
$^4S_{3/2}$
0.97 µm
$^4F_{9/2}$
$^4I_{9/2}$
8 msec
$^4I_{11/2}$
ENERGY
10 msec
$^4I_{13/2}$
1.55 µm
0.97 µm
$^4I_{15/2}$
Er^{3+}

FIG.4

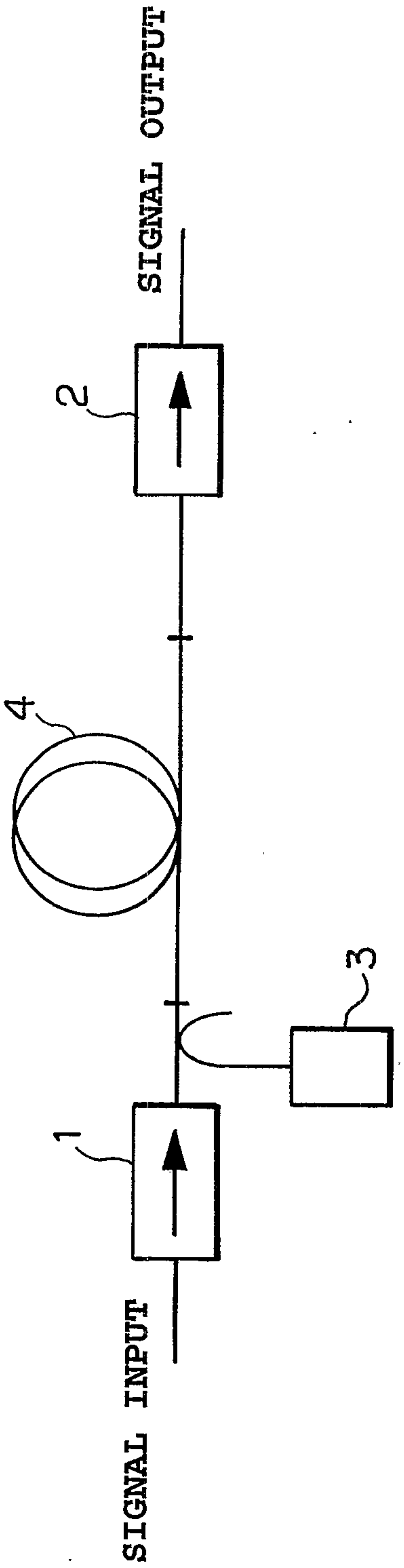


FIG.5

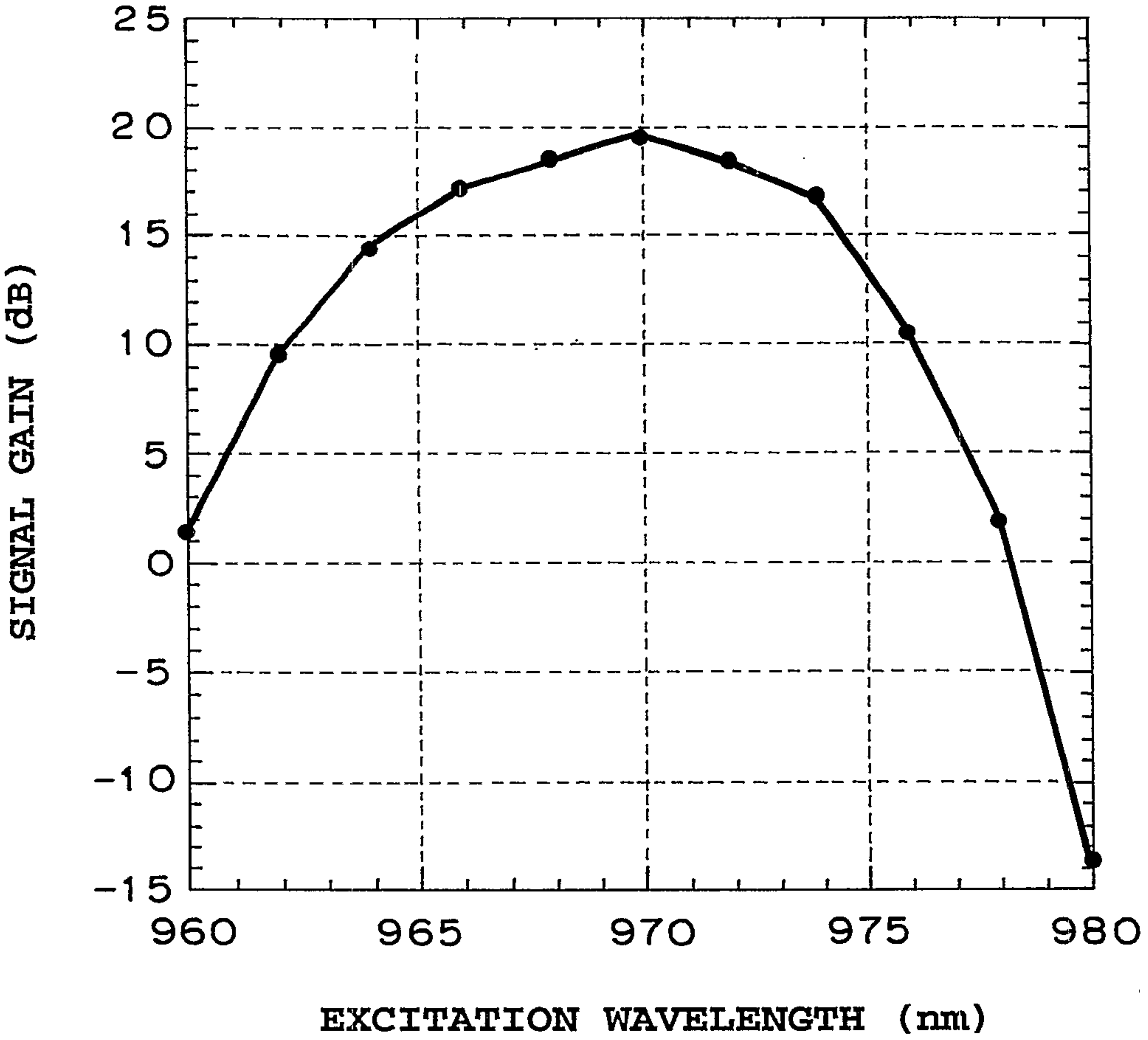

25
20
15
10
5
0
-5
-10
-15
SIGNAL GAIN (dB)
960
965
970
975
980
EXCITATION WAVELENGTH (nm)

FIG.6

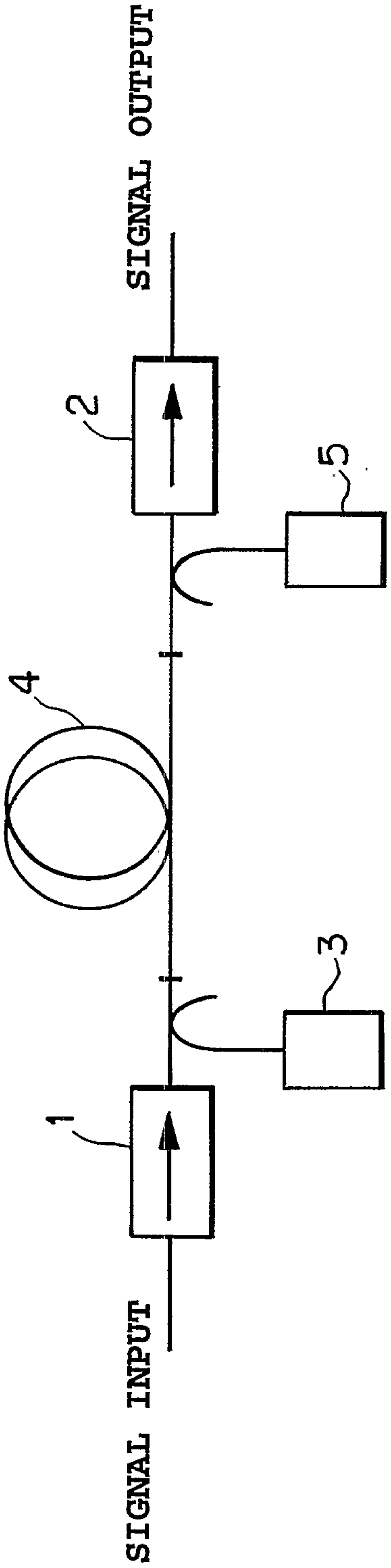


FIG.7

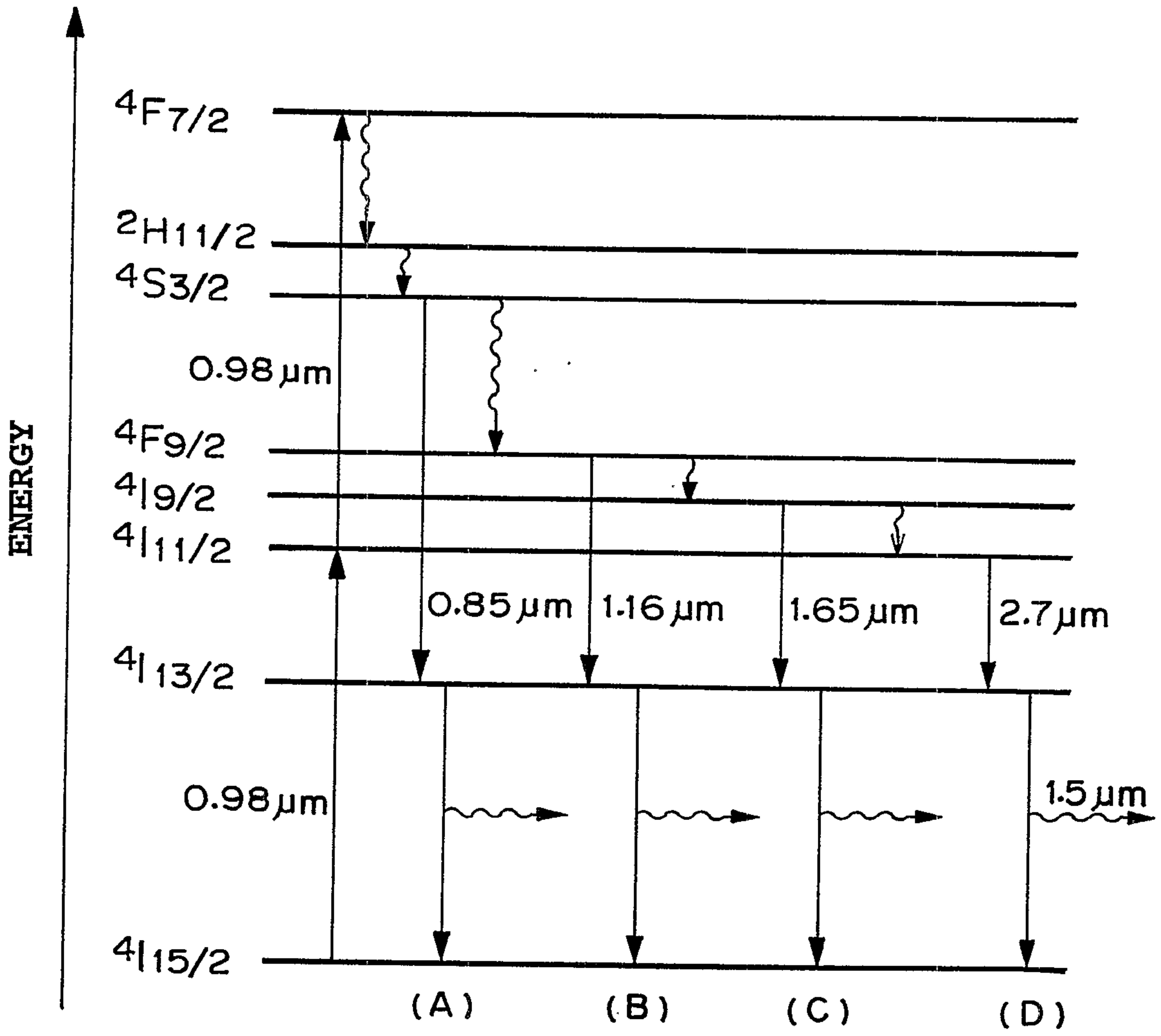

ENERGY
$^4F_{7/2}$
$^2H_{11/2}$
$^4S_{3/2}$
0.98 μm
$^4F_{9/2}$
$^4I_{9/2}$
$^4I_{11/2}$
0.85 μm
1.16 μm
1.65 μm
2.7 μm
$^4I_{13/2}$
0.98 μm
1.5 μm
$^4I_{15/2}$
(A)
(B)
(C)
(D)

FIG.8

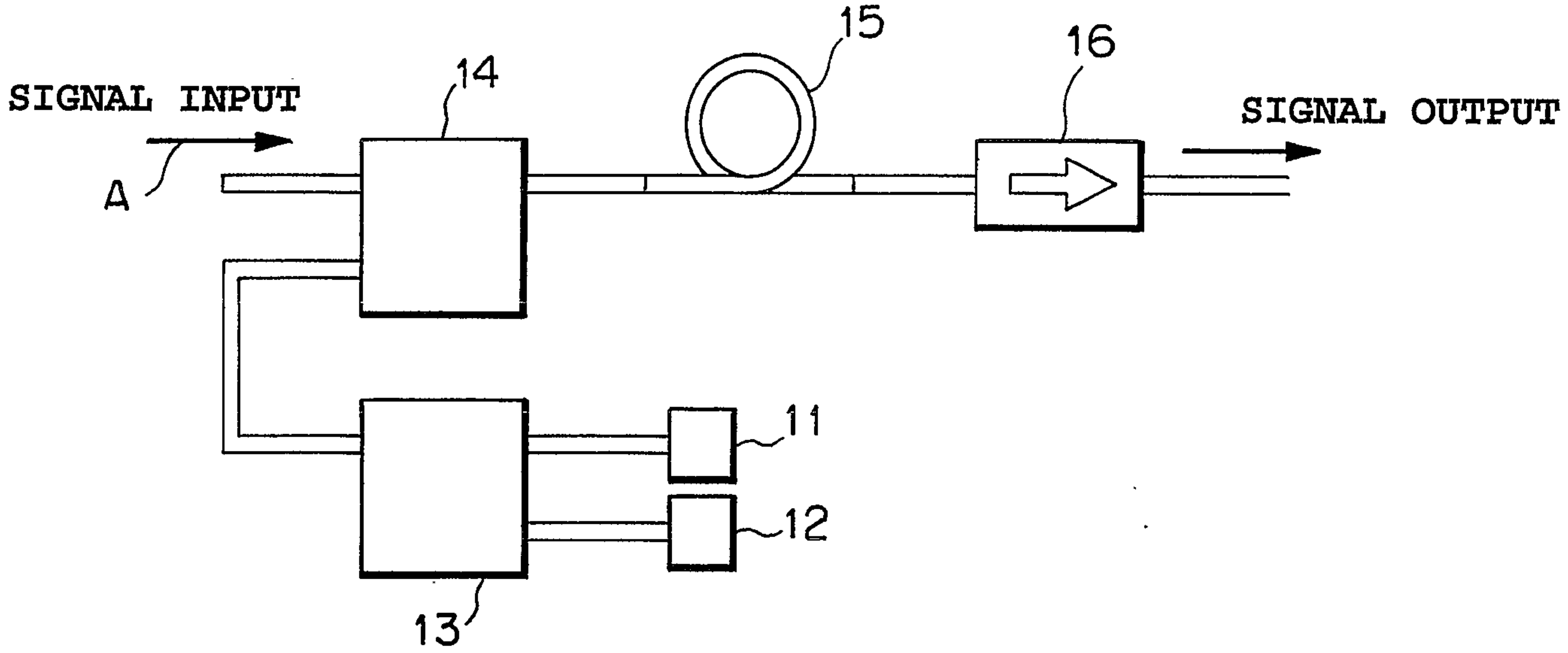


FIG.9

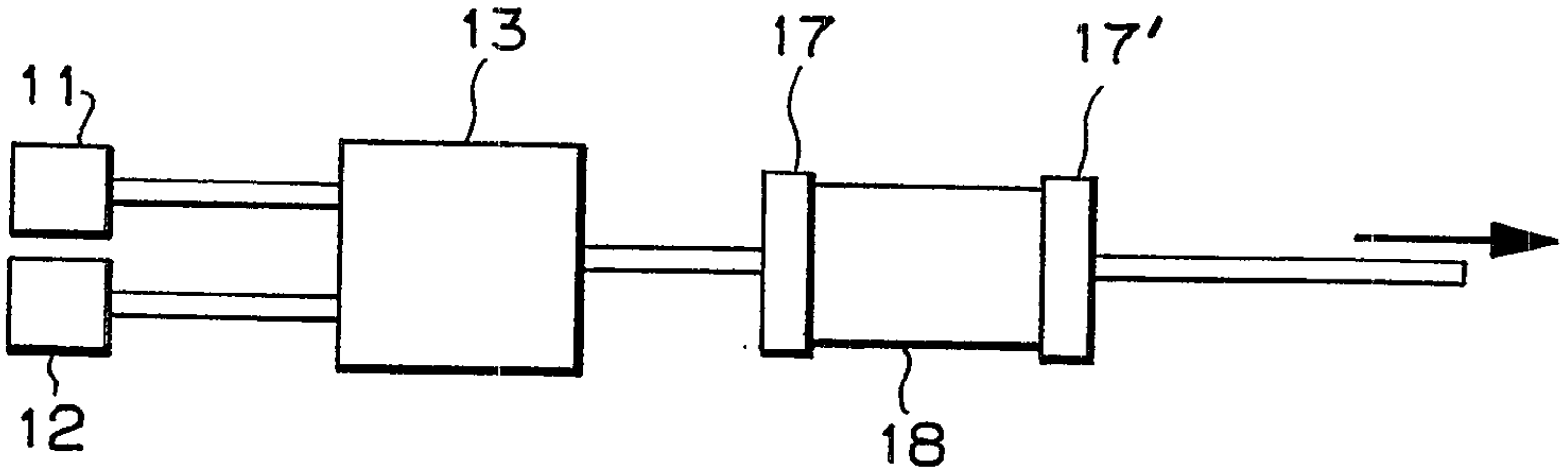


FIG.10

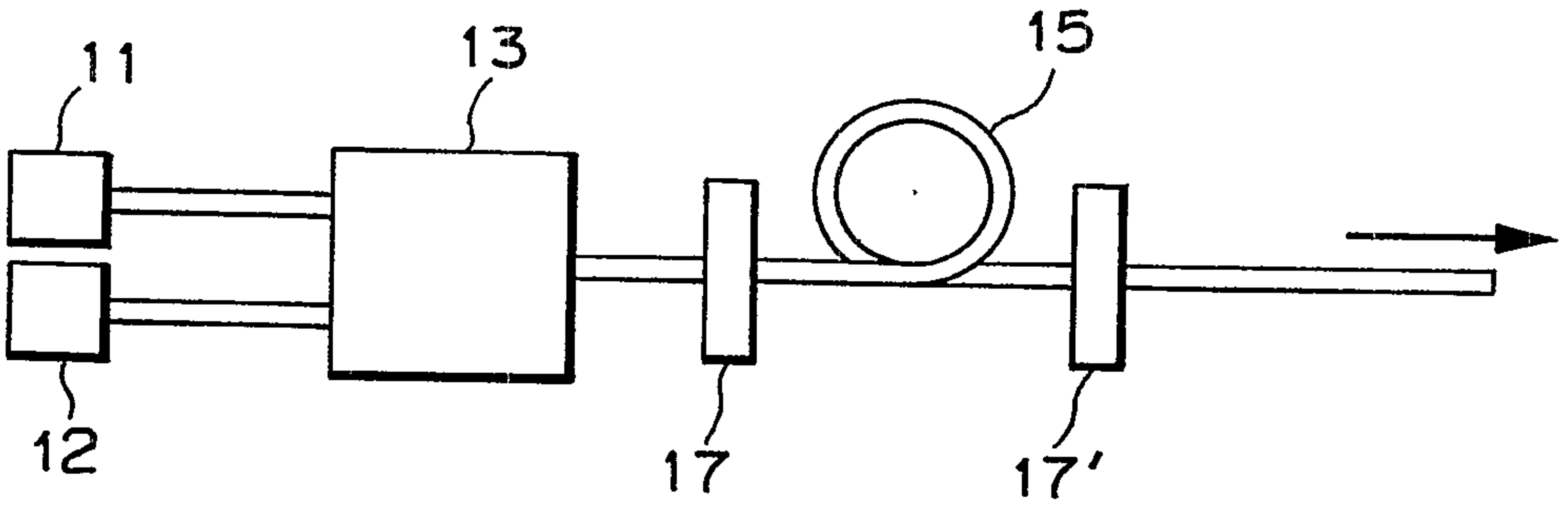


FIG.11

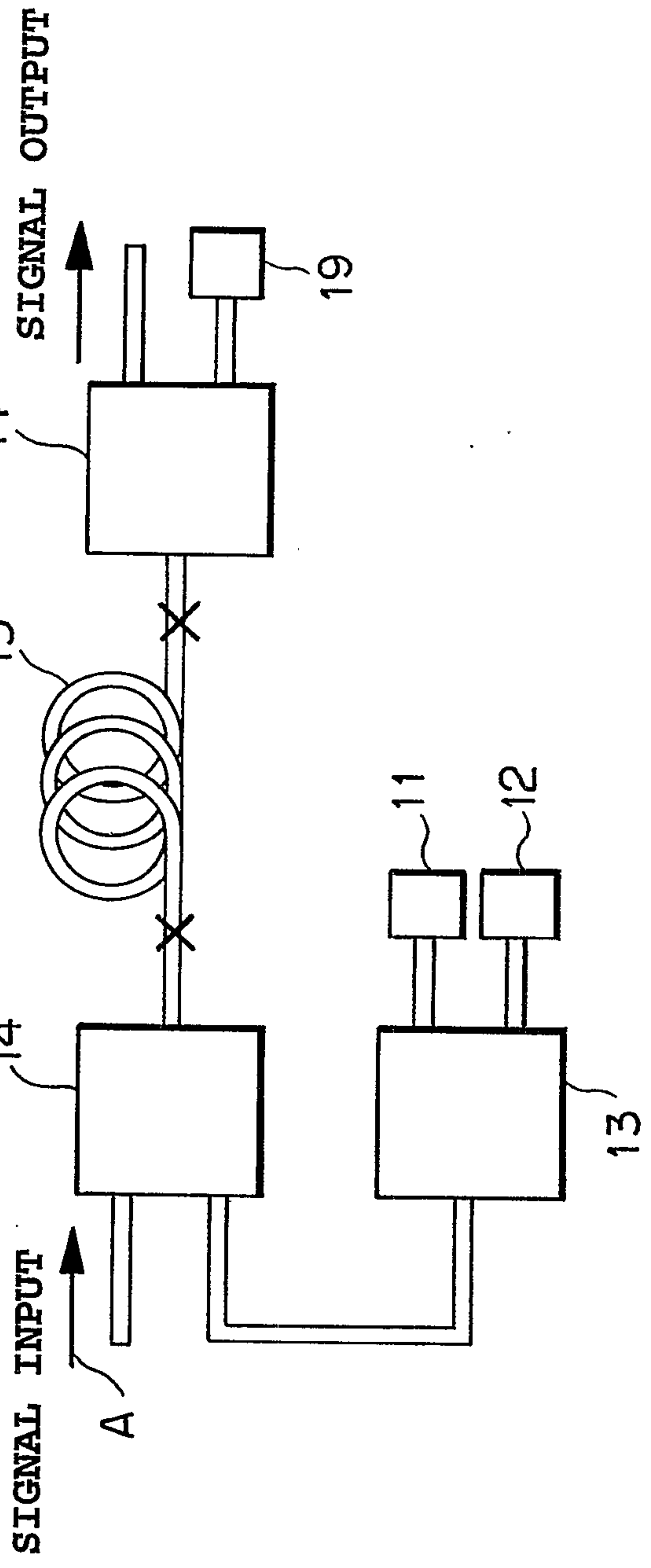


FIG.12

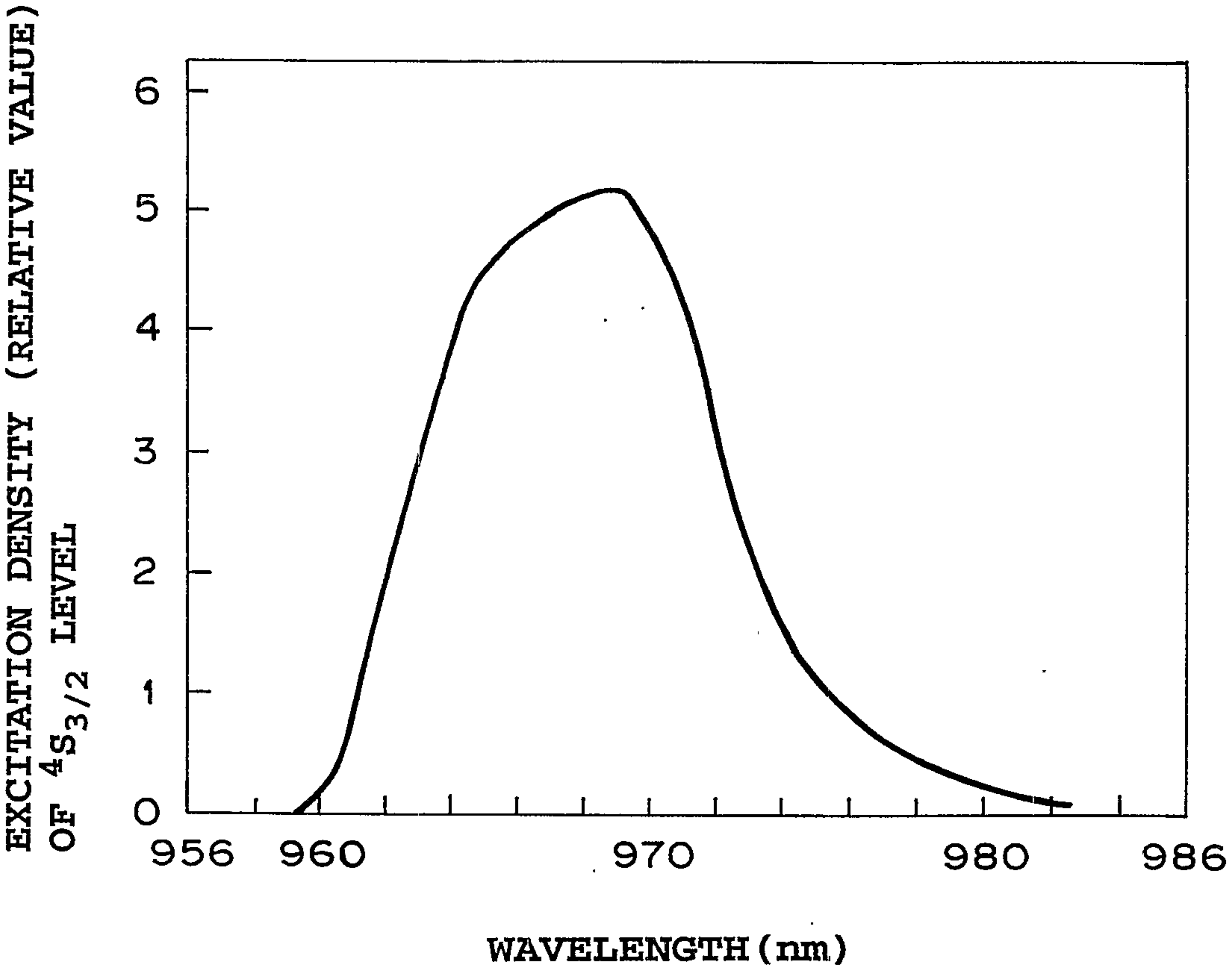

EXCITATION DENSITY (RELATIVE VALUE) OF $^4S_{3/2}$ LEVEL
6
5
4
3
2
1
0
956
960
970
980
986
WAVELENGTH (nm)

FIG.13

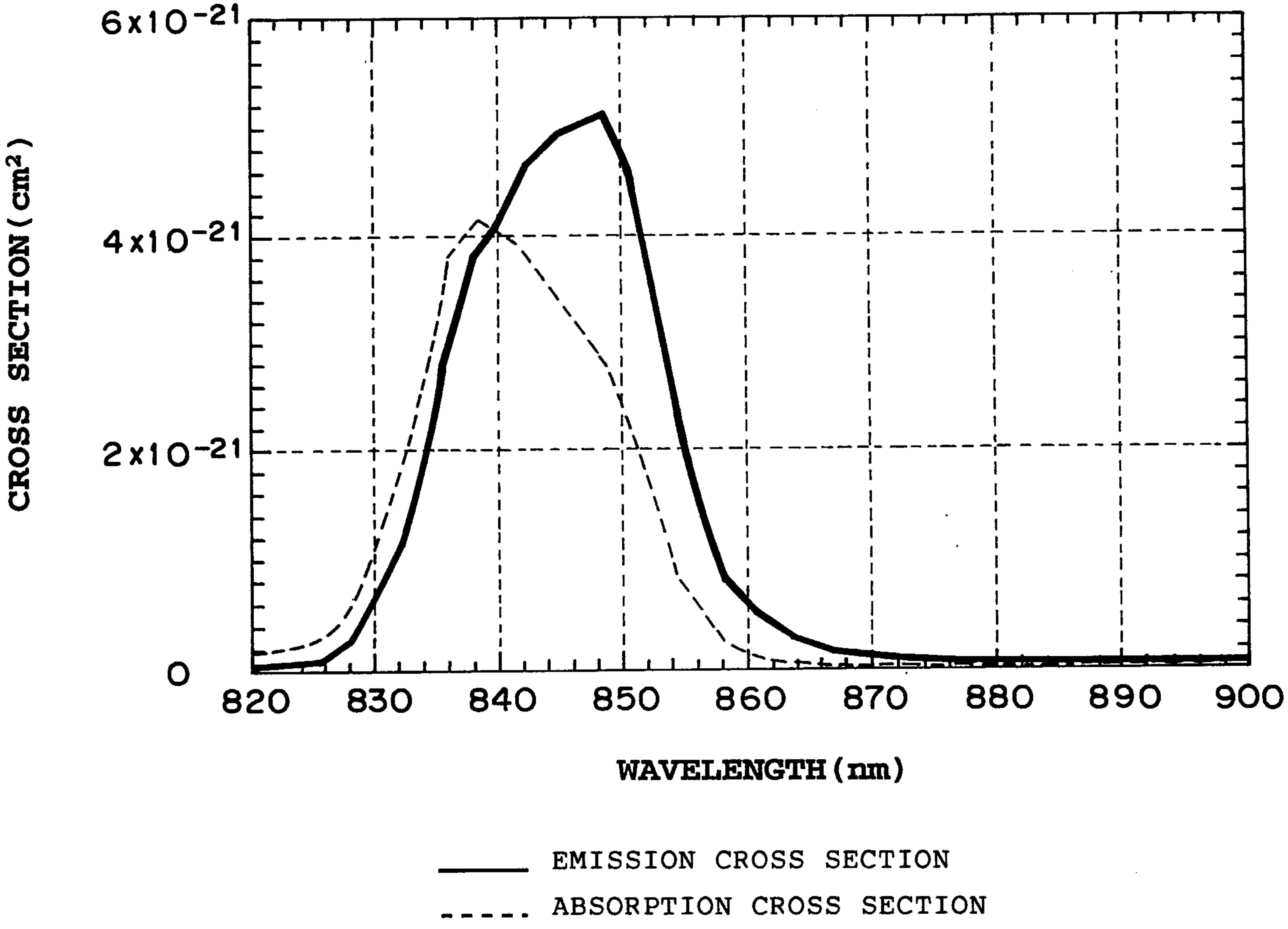

6x10^{-21}
4x10^{-21}
2x10^{-21}
0
CROSS SECTION (cm^2)
820
830
840
850
860
870
880
890
900
WAVELENGTH (nm)
EMISSION CROSS SECTION
ABSORPTION CROSS SECTION

FIG.14

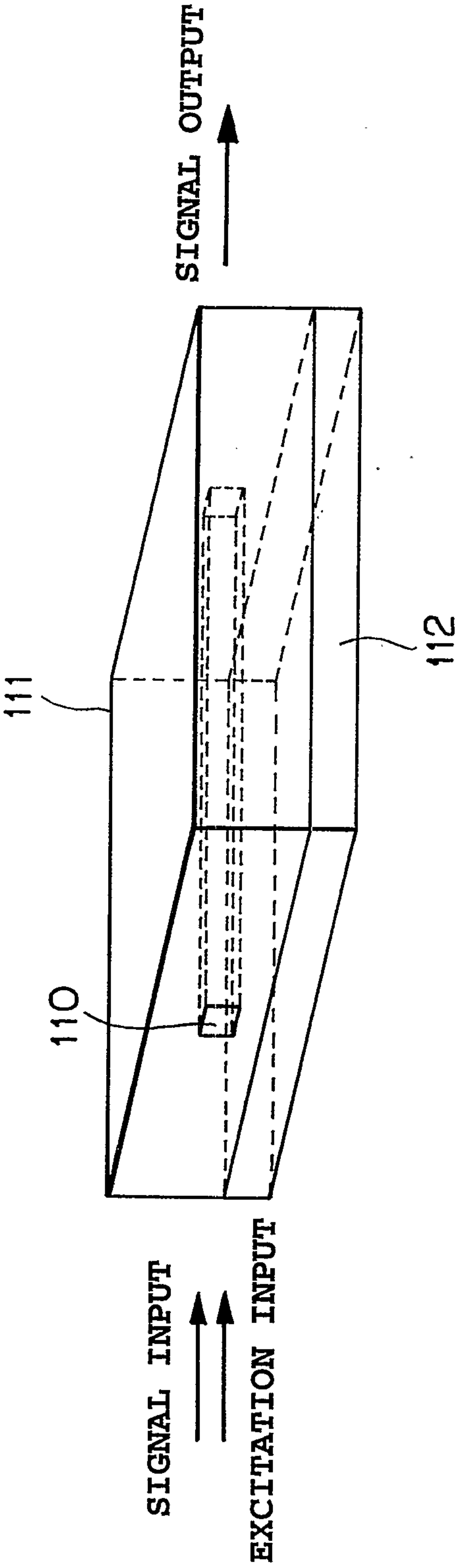
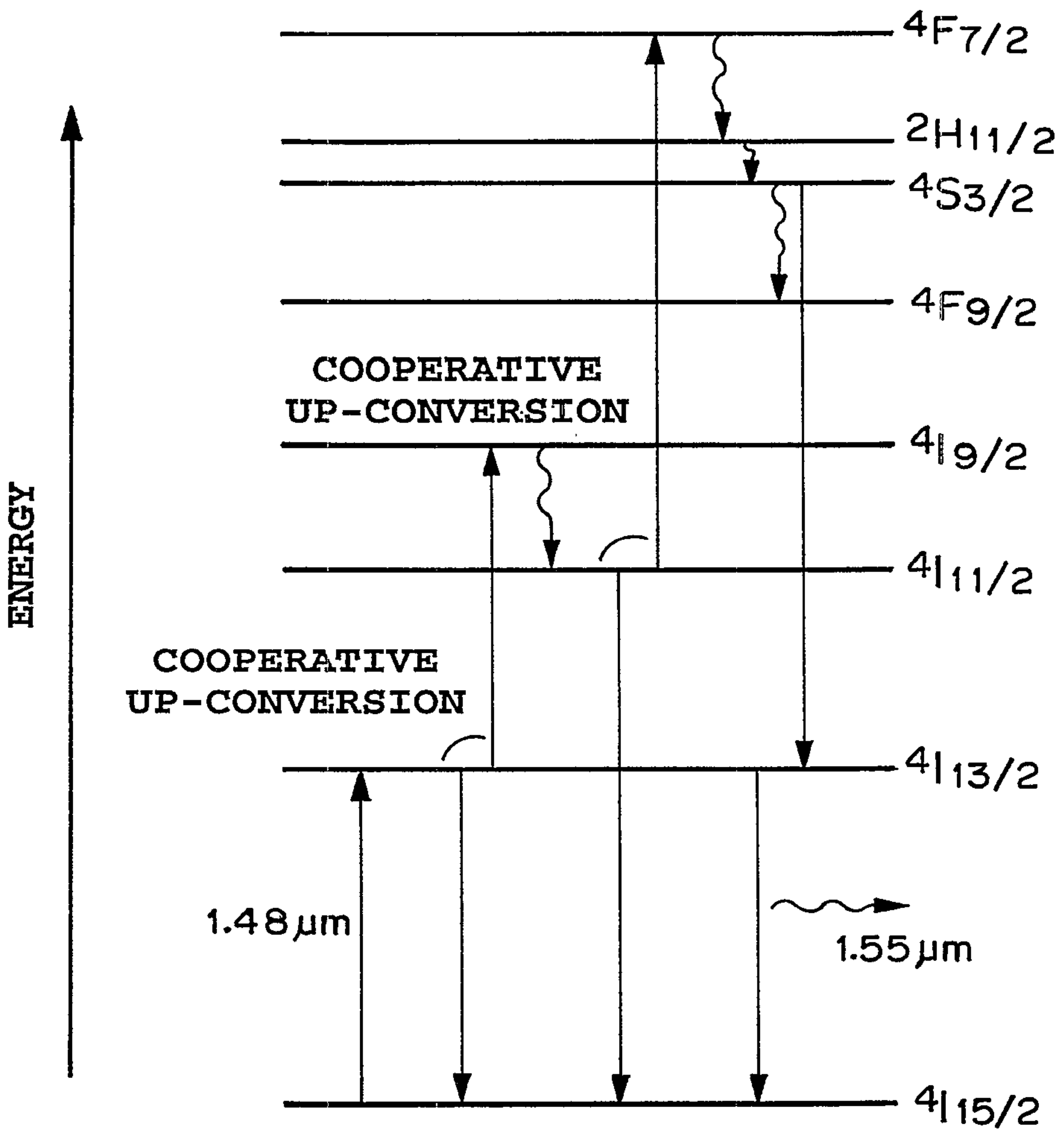
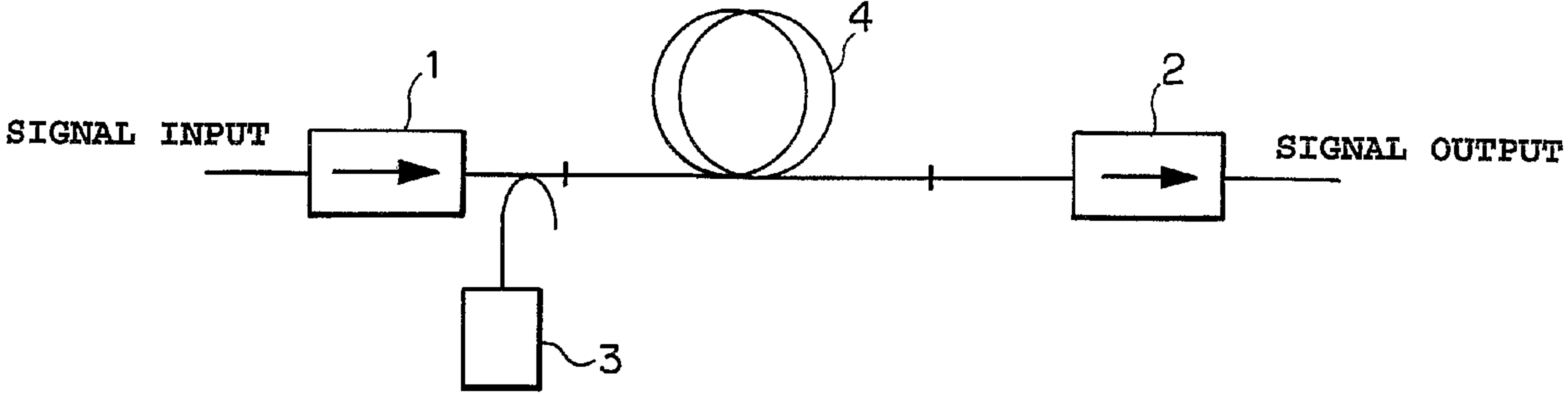


FIG.15



$^4F_{7/2}$
$^2H_{11/2}$
$^4S_{3/2}$
$^4F_{9/2}$
$^4I_{9/2}$
$^4I_{11/2}$
$^4I_{13/2}$
$^4I_{15/2}$
COOPERATIVE UP-CONVERSION
COOPERATIVE UP-CONVERSION
ENERGY
1.48 μm
1.55 μm

FIG. 16


SIGNAL INPUT
1
4
2
SIGNAL OUTPUT
3